Neutrinos: towards an understanding of the origin of neutrino masses and mixing beyond the Standard Model

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Joint Experimental-Theoretical Physics Seminar
Fermilab

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IPPP – Durham University

Outline

1. Present status of neutrino parameters

2. Neutrinos and physics BSM
   - The origin of neutrino masses
   - The problem of leptonic flavor

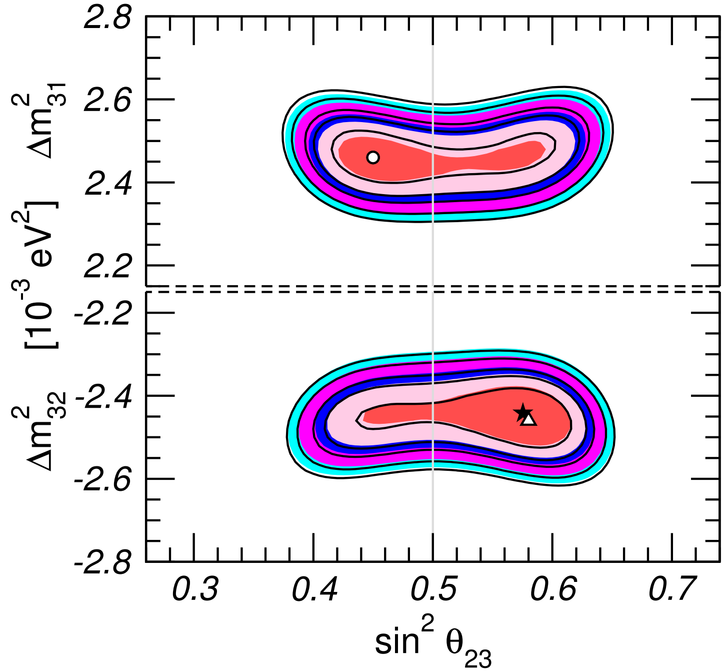
3. How to discriminate between different models of neutrino masses:
   - CLFV
   - Leptogenesis

4. The new mass scale and its tests

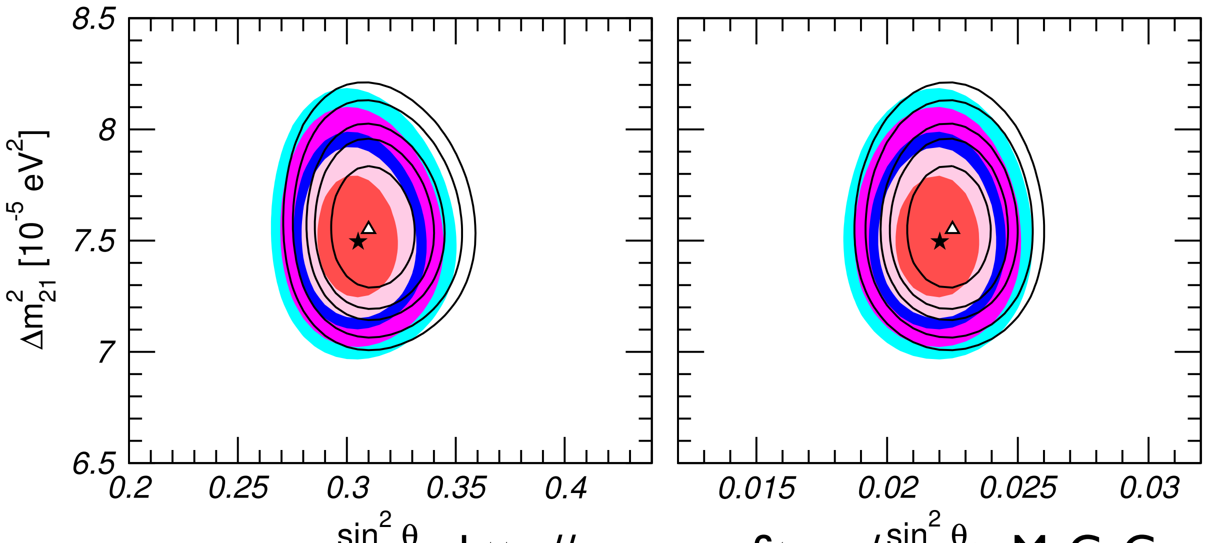
5. Conclusions

Neutrino properties after Neutrino 2014

NuFIT 1.3 (2014)

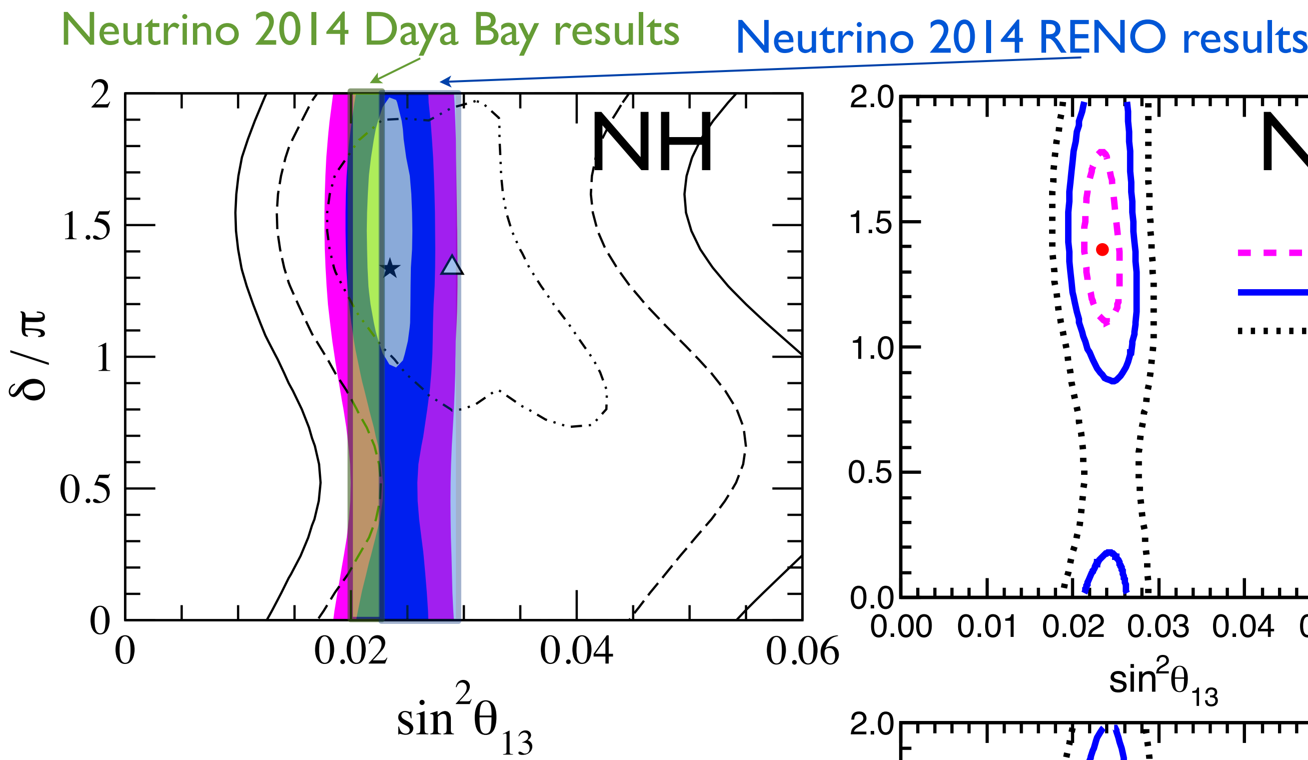


	Free Fluxes + RSBL	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.77}_{-0.74}$	$31.30 \to 35.90$
$\sin^2\theta_{23}$	$\left[0.451^{+0.001}_{-0.001}\right] \oplus 0.577^{+0.027}_{-0.035}$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$\left[42.2^{+0.1}_{-0.1}\right] \oplus 49.4^{+1.6}_{-2.0}$	$38.4 \to 53.3$
$\sin^2\theta_{13}$	$0.0219^{+0.0010}_{-0.0011}$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.52^{+0.20}_{-0.21}$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	251^{+67}_{-59}	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$\left[+2.458^{+0.002}_{-0.002}\right]$	$+2.325 \to +2.599$
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.448^{+0.047}_{-0.047}$	$-2.590 \to -2.307$

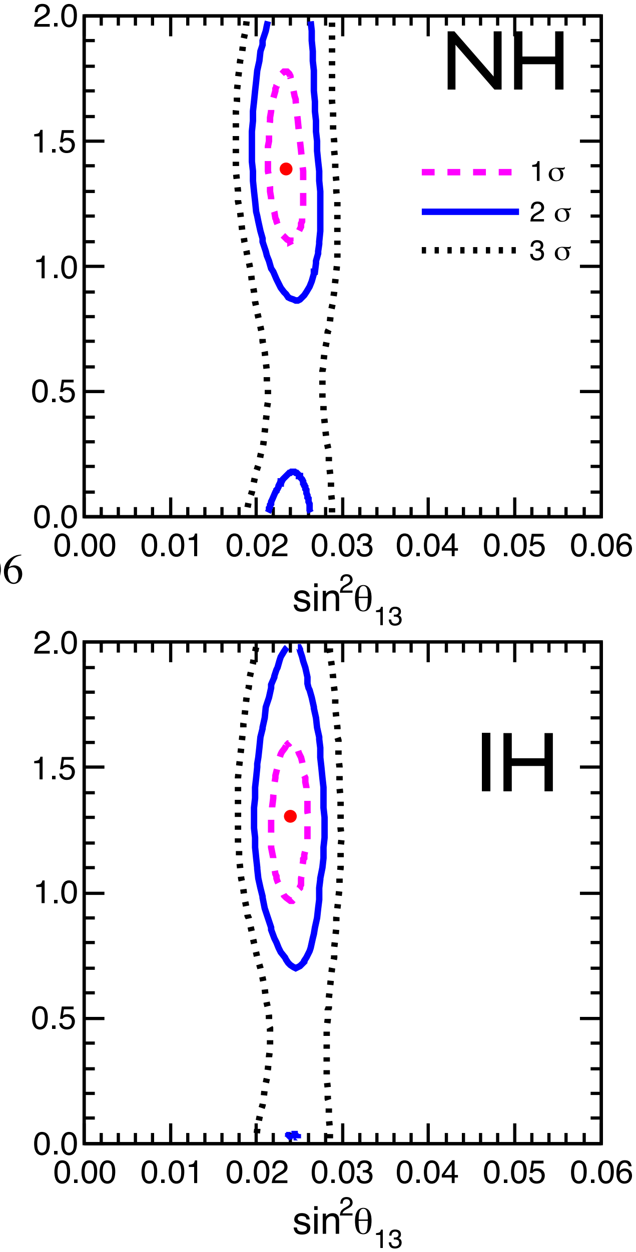


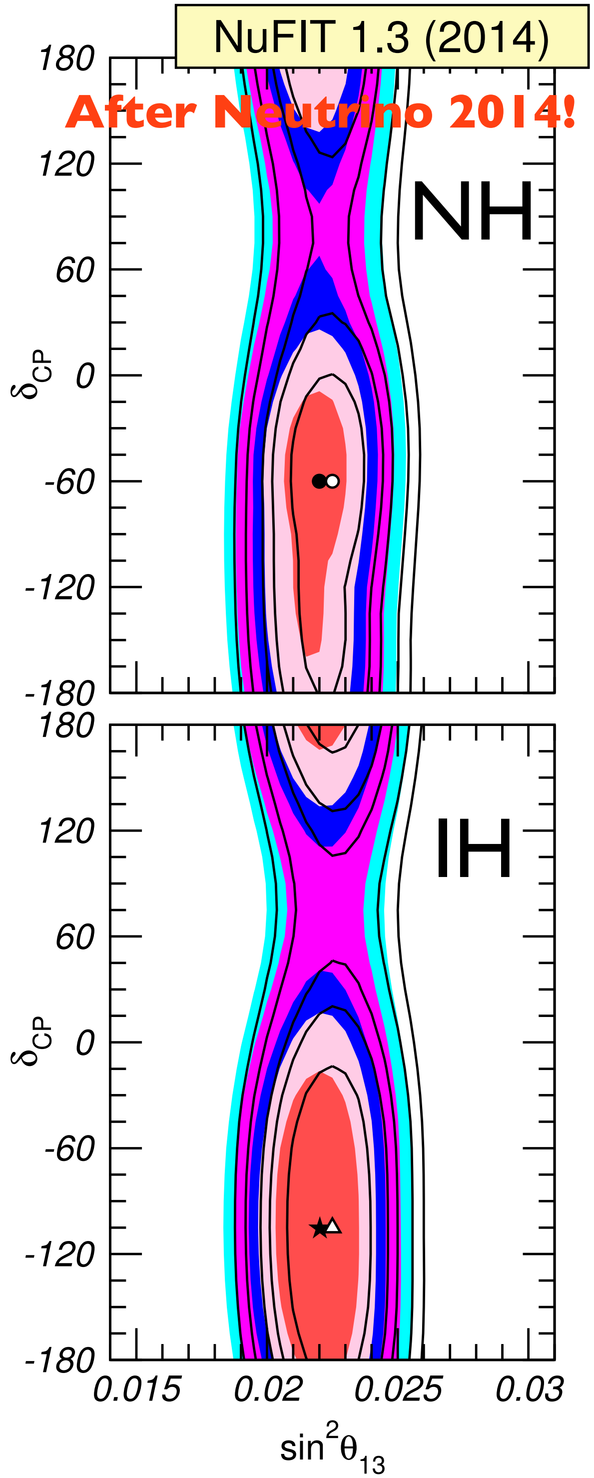
2 mass squared differences and 3 sizable mixing angles

http://www.nu-fit.org/ M. C. Gonzalez-Garcia et al., 1209.3023



D.V. Forero et al., 1405.7540



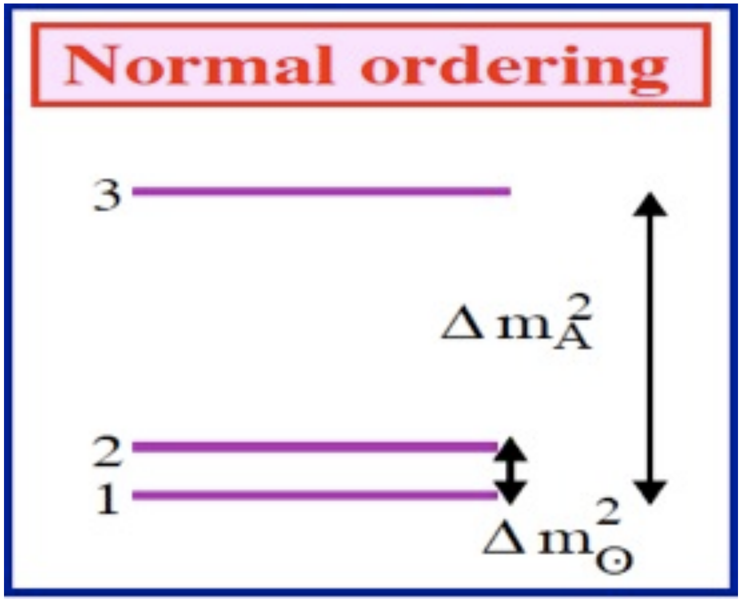


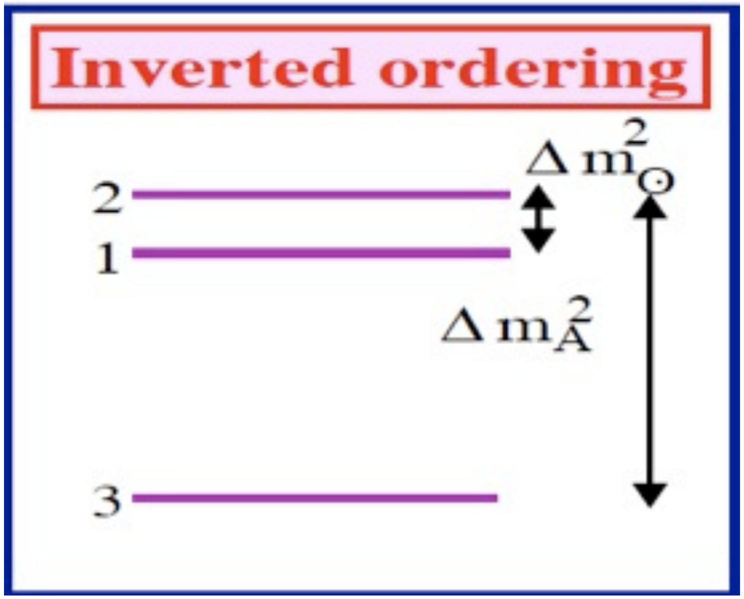
There is a slight preference for CP-violation, which is mainly due to the combination of T2K and reactor neutrino data.

F. Capozzi et al., 1312.2878

NuFit: M. C. Gonzalez-Garcia et al., 1209.3023

$\Delta m_{\rm s}^2 \ll \Delta m_{\rm A}^2$ implies at least 3 massive neutrinos.





$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm sol}^2}$$
$$m_3 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2 - \Delta m_{\rm sol}^2}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

Measuring the masses requires:

- the mass scale: $m_{\rm min}$
- the mass ordering.

Phenomenology questions for the future

- **1. What is the nature of neutrinos?**
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **3. Is there CP-violation?**
- **4. What are the precise values of mixing angles?**
- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

Very exciting experimental programme now and for the future.

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MINOS, T2K, NOvA, LBNE, LBNO, T2HK, nuFACT... MINERvA

- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

MINOS+, MiniBooNE, MicroBooNE

Very exciting experimental programme now and for the future.

Neutrino oscillations imply that neutrinos have mass and mix.

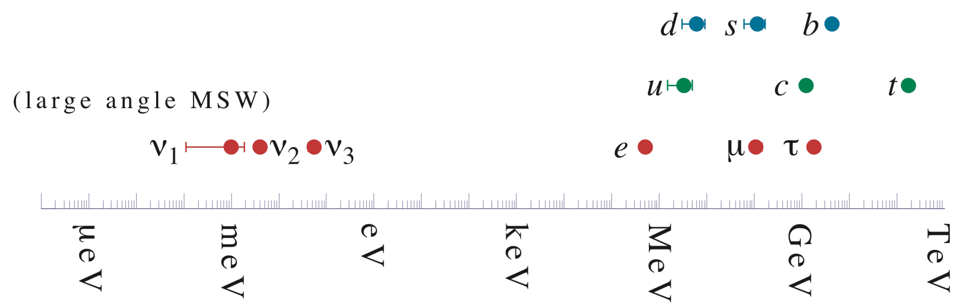
First evidence of physics beyond the SM.

The ultimate goal is to understand
- where do neutrino masses come from?
- what is the origin of leptonic mixing?

Open window on Physics beyond the SM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



Why neutrinos have mass?
and why are they so lighter?
and why their hierarchy is at most mild?

2. Problem of flavour

$$\begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

$$\begin{pmatrix} 0.8 & 0.5 & 0.16 \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & 0.7 \end{pmatrix}$$

Why leptonic mixing is so different from quark mixing?

This points towards a different origin of neutrino masses and mixing from the ones for quarks: a different window on the physics BSM.

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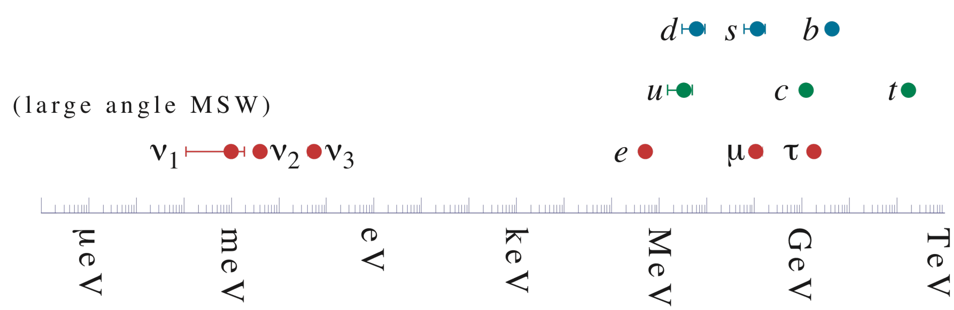

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Neutrino Masses in the SM and beyond

In the SM, neutrinos do not acquire mass and mixing:

- like the other fermions as there are no right-handed neutrinos.

$$m_e \bar{e}_L e_R \qquad\qquad m_\nu \bar{\nu}_L \cancel{\nu_R}$$

Solution: Introduce ν_R for Dirac masses

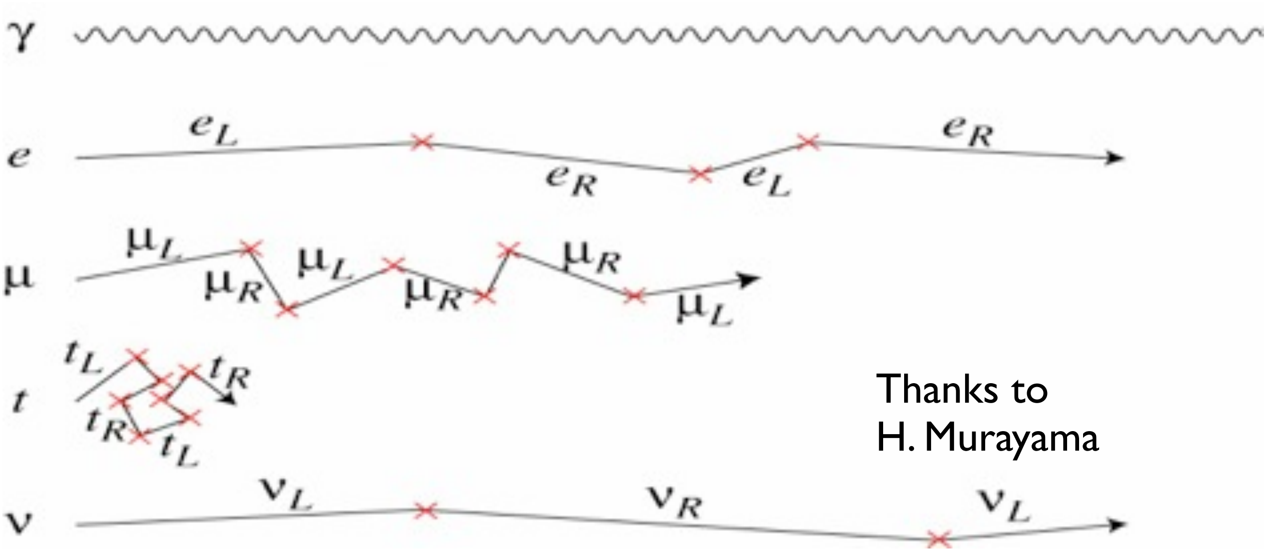
- they do not have a Majorana mass term

$$M \nu_L^T C \nu_L$$

as this term breaks the SU(2) gauge symmetry.
This term breaks Lepton Number.

Dirac Masses

If we introduce a right-handed neutrino, then an interaction with the Higgs boson is allowed.



Thanks to
H. Murayama

This conserves lepton number!

$$\boxed{\mathcal{L} = -y_\nu \bar{L} \cdot \tilde{H} \nu_R + \text{h.c.}}$$

Masses and Mixing emerge from diagonalising this matrix.

$$m_D = y_\nu v = V m_{\text{diag}} U^\dagger$$

$$n_L = U^\dagger \nu_L \quad n_R = V^\dagger \nu_R$$

This is the mixing matrix which enters in neutrino oscillations.

$$y_\nu \sim \frac{\sqrt{2} m_\nu}{v_H} \sim \frac{0.2 \text{ eV}}{200 \text{ GeV}} \sim 10^{-12}$$

Tiny couplings!

Many theorists consider this explanation of neutrino masses not satisfactory. We would expect this Yukawa couplings to be similar to the ones in the quark sector:

1. why the coupling is so small????
2. why the mixings are large? (instead of small as in the quark sector)
3. why neutrino masses have at most a mild hierarchy if they are not quasi-degenerate? instead of what happens to quarks?

Majorana Masses

In order to have an SU(2) invariant mass term for neutrinos, it is necessary to introduce a Dimension 5 operator (or to allow new scalar fields, e.g. a triplet):

$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M} = \frac{\lambda v_H^2}{M} \nu_L^T C^\dagger \nu_L$$

D=5 term

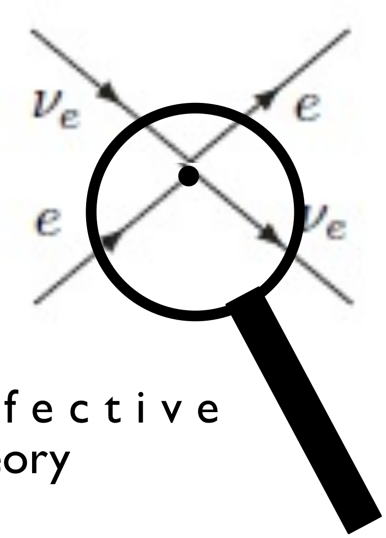
Weinberg operator

Lepton number violation!

Masses and mixing come from diagonalising the mass matrix

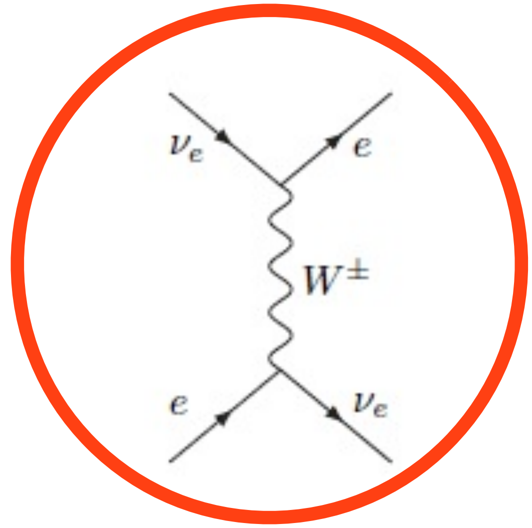
$$\boxed{M_M = (U^\dagger)^T m_{\mathrm{diag}} U^\dagger} \qquad \boxed{n_L = U^\dagger \nu_L}$$

If neutrino are Majorana particles, a **Majorana mass** can arise as the low energy realisation of a higher energy theory (new mass scale!).



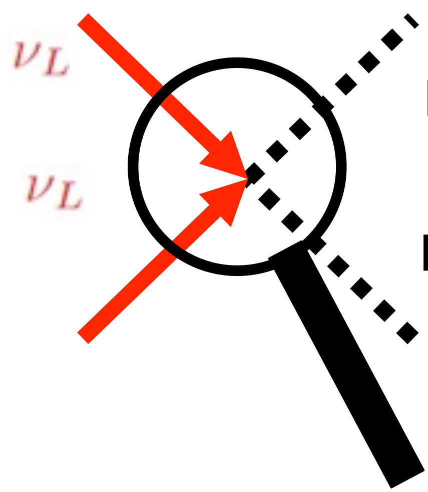
effective theory

$$\mathcal{L} \propto G_F(\bar{e}_L\gamma_\mu\nu_L)(\bar{\nu}_L\gamma^\mu e_L)$$



Standard Model:
W exchange

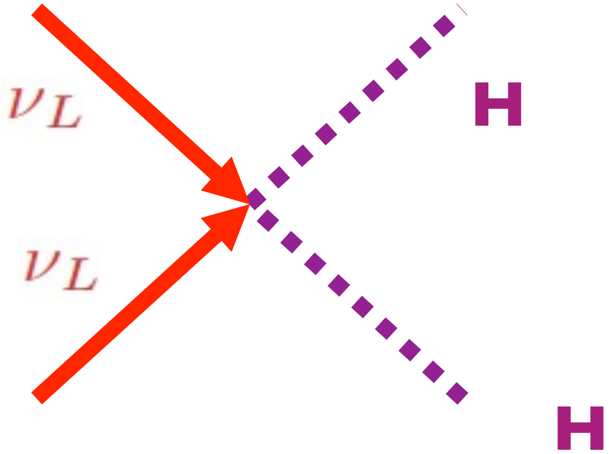
$$\mathcal{L}_{SM} \propto g\bar{\nu}_L\gamma^\mu e_L W_\mu \Rightarrow G_F \propto \frac{g^2}{m_W^2}$$



Neutrino mass

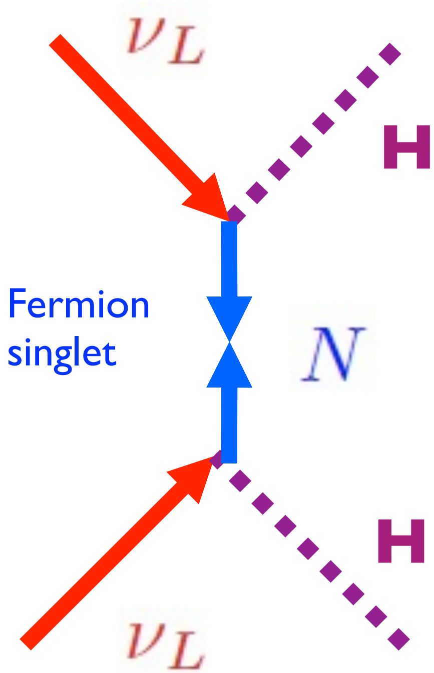
$$-\mathcal{L} = \lambda\frac{L\cdot HL\cdot H}{M}$$

New theory:
new particle
exchange with
mass M



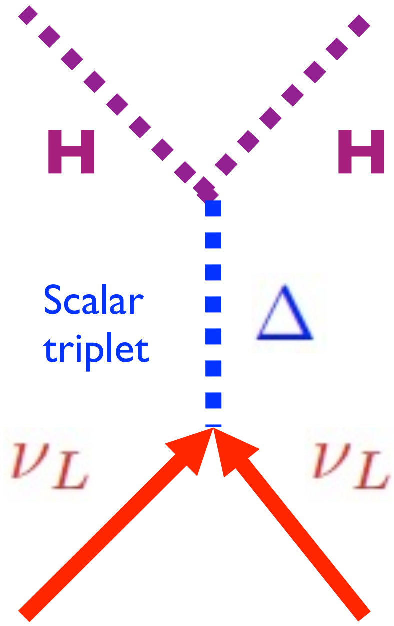
$$-\mathcal{L} = \lambda \frac{L \cdot H L \cdot H}{M}$$

See-saw Type I



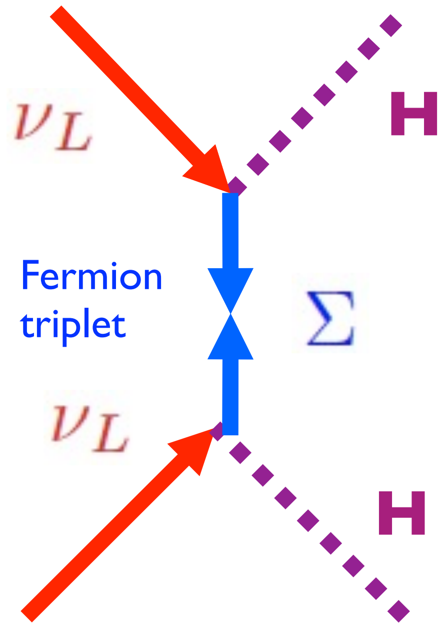
Minkowski, Yanagida, Glashow, Gell-Mann, Ramond, Slansky, Mohapatra, Senjanovic

See-saw Type II



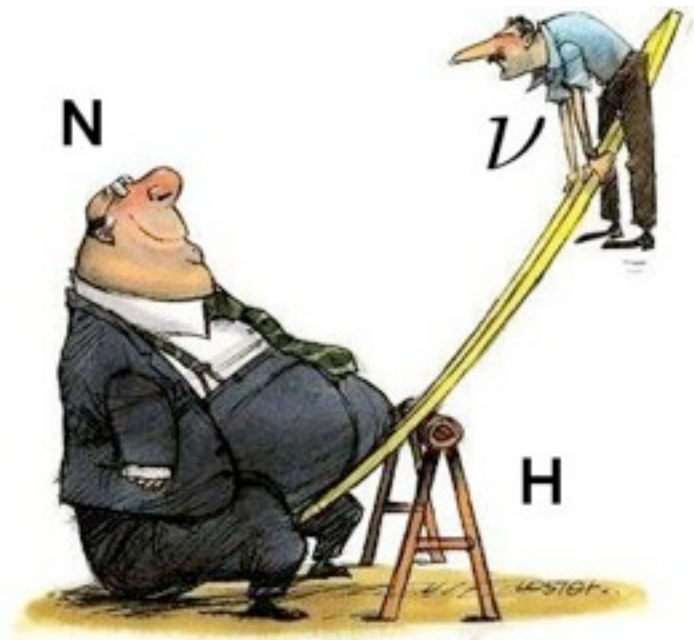
Magg, Wetterich, Lazarides, Shafi. Mohapatra, Senjanovic, Schecter, Valle

See-saw Type III



Ma, Roy, Senjanovic, Hambye

Neutrino masses BSM: see saw mechanism type I



- Introduce a right handed neutrino **N**
- Couple it to the Higgs

$$\mathcal{L} = -Y_\nu \bar{N} L \cdot H - 1/2 \bar{N}^c M_R N$$

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M_N \end{pmatrix} \Rightarrow m_\nu = \frac{Y_\nu^2 v_H^2}{M_N} \sim \frac{1\ \mathrm{GeV}^2}{10^{10}\mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic

See-saw type I models can be embedded in GUT theories and explain the baryon asymmetry via leptogenesis.

The resulting massive states are Majorana particles and

$$\nu_{\text{active}} = U_i \, n_{i,\text{light}} + U_k \, N_{k,\text{heavy}}$$

Non unitarity

Active and heavy neutrino mixing: $m_\nu \simeq \frac{m_D^2}{M} \simeq \sin^2\theta M$

Pros:

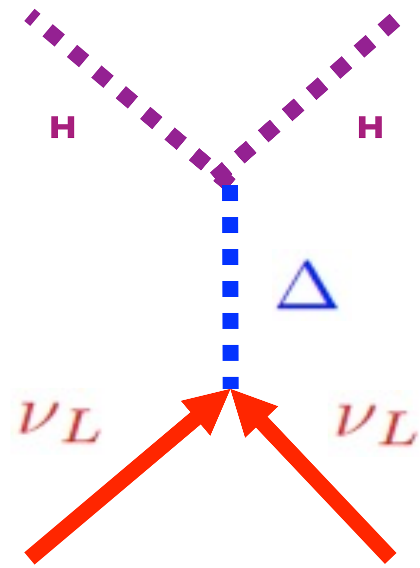
- they explain "naturally" the smallness of masses.
- can be embedded in GUT theories!
- have several phenomenological consequences (depending on the mass scale), e.g. leptogenesis, LFV

Cons:

- the new particles are typically too heavy to be produced at colliders (but TeV scale see-saws)
- the mixing with the new states are tiny
- many more parameters than measurable
- in general: difficult to test

Neutrino masses BSM: see saw mechanism type II

We introduce a Higgs triplet which couples to the Higgs and left handed neutrinos. It has hypercharge 2.



$$\mathcal{L}_\Delta \propto y_\Delta L^T C^{-1} \sigma_i \Delta_i L + \mathrm{h.c.}$$

with $$\Delta_i = \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix}$$

Once the Higgs triplet gets a vev, Majorana neutrino masses arise:

$$\boxed{m_\nu \sim y_\Delta v_\Delta}$$

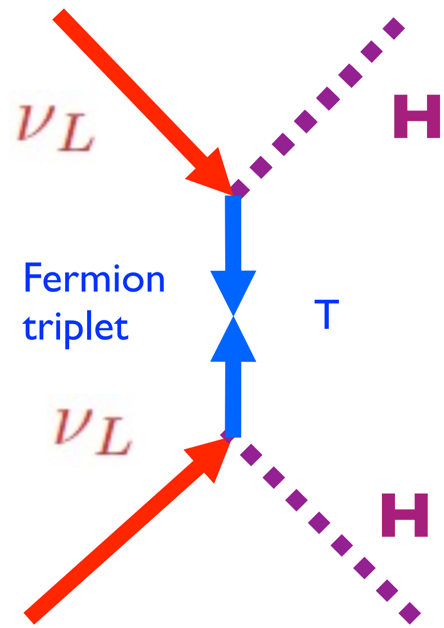
Cons: why the vev is very small?
Pros: the component of the Higgs triplet could tested directly at the LHC.

Neutrino masses BSM: see saw mechanism type III

We introduce a fermionic triplet which has hypercharge 0.

$$\mathcal{L}_T \propto y_T \bar{L} \sigma H \cdot T + \mathrm{h.c.}$$

with $$T = \begin{pmatrix} T^0 & T^+ \\ T^- & -T^0 \end{pmatrix}$$



Majorana neutrino masses are generated as in see-saw type I:

$$\boxed{m_\nu \simeq -y_T^T M_T^{-1} y_T v_H^2}$$

Pros: the component of the fermionic triplet have gauge interactions and can be produced at the LHC
Cons: why the mass of T is very large?

Extensions of the see saw mechanism

Models in which it is possible to lower the mass scale (e.g. TeV or below), keeping large Yukawa couplings and sizable mixing have been studied.

Let's introduce two right-handed singlet neutrinos.

$$\mathcal{L} = Y\bar{L} \cdot HN_1 + Y_2\bar{L} \cdot HN_2^c + \Lambda\bar{N}_1 N_2 + \mu' N_1^T C N_1 + \mu N_2^T C N_2$$

$$\begin{pmatrix} 0 & Yv & Y_2 v \\ Yv & \mu' & \Lambda \\ Y_2 v & \Lambda & \mu \end{pmatrix}$$

See e.g. Gavela et al., 0906.1461; Ibarra, Molinaro, Petcov, 1103.6217; Kang, Kim, 2007; Majee et al., 2008; Mitra, Senjanovic, Vissani, 1108.0004; Malinsky, Romao, Valle, 2005

$$m_{tree} \simeq -m_D^T M^{-1} m_D \simeq \frac{v^2}{2(\Lambda^2 - \mu'\mu)} \left(\mu Y_1^T Y_1 + \epsilon^2 \mu' Y_2^T Y_2 - \Lambda\epsilon (Y_2^T Y_1 + Y_1^T Y_2)\right)$$

Small neutrino masses emerge due to cancellations between the contributions of the two sterile neutrinos (typically associated to small breaking of some L).

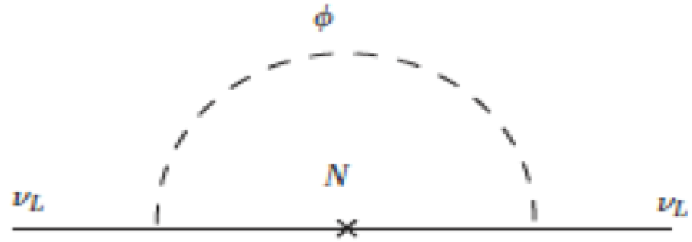
Examples: inverse see-saw, extended see-saw...

Other models of neutrino masses

Radiative masses

If neutrino masses emerge via loops, in models in which Dirac masses are forbidden, there is an additional suppression.

Some of these models have also dark matter candidates.



$$m_\nu \propto \frac{g^2}{16\pi^2} f(M, \mu_\phi^2)$$

R-parity violating SUSY

In the MSSM, there are no neutrino masses. But it is possible to introduce terms which violate R (and L).

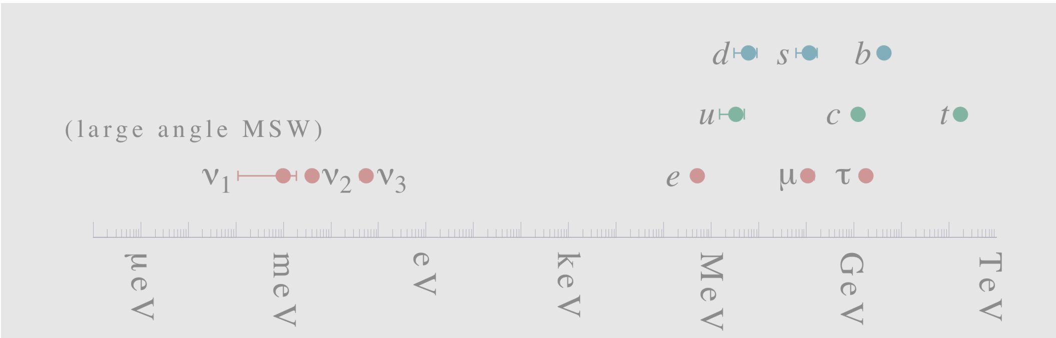
$$V = \ldots - \mu H_1 H_2 + \epsilon_i \tilde{L}_i H_2 + \lambda'_{ijk} \tilde{L}_i \tilde{L}_j \tilde{E}_k + \ldots$$

The bilinear term induces mixing between neutrinos and higgsino and therefore neutrino masses, the trilinear term induces masses at the loop-level.

Open window on Physics beyond the SM

Neutrinos give a different perspective on physics BSM.

1. Origin of masses



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Why leptonic mixing is so different from quark mixing?

This points towards a different origin of neutrino masses and mixing from the ones for quarks: a different window on the physics BSM.

Values of mixing angles suggest an underlying pattern.

Example: Bimaximal mixing

$$\mathcal{U}_0 = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & -\frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} + \begin{pmatrix} \mathcal{O}(0.1) & -\mathcal{O}(0.1) & \mathcal{O}(0.1) \\ \mathcal{O}(0.1) & \mathcal{O}(0.1) & -\mathcal{O}(0.01) \\ -\mathcal{O}(0.1) & -\mathcal{O}(0.1) & \mathcal{O}(0.01) \end{pmatrix}$$

In this case, theta23 requires small perturbations but theta12 and theta13 large ones.

Example: Tribimaximal mixing

$$\mathcal{U}_0 = \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} + \begin{pmatrix} \mathcal{O}(0.001) & -\mathcal{O}(0.01) & \mathcal{O}(0.1) \\ \mathcal{O}(0.1) & \mathcal{O}(0.05) & -\mathcal{O}(0.01) \\ -\mathcal{O}(0.1) & -\mathcal{O}(0.05) & \mathcal{O}(0.01) \end{pmatrix}$$

Harrison, Perkins, Scott

Large corrections to theta13 are needed.

Three other patterns: golden ratio ($\tan\theta_{12}|_0 = \frac{2}{1+\sqrt{5}}$), and hexagonal ($\theta_{12}|_0 = 30^o$) mixing patterns.

Masses and mixing from the mass matrix

Recall that the mixing matrix arises from the diagonalisation of the mass matrix

$$\boxed{M_M = (U^\dagger)^T m_{\rm diag} U^\dagger} \quad \Rightarrow \quad \boxed{n_L = U^\dagger \nu_L}$$

so the form of the mass matrix will lead to specific values of the masses (mass ordering) and angles.

Example. In the diagonal basis for the leptons

$$\mathcal{M}_\nu = \begin{pmatrix} a & b \\ b & c \end{pmatrix}$$

the angle is $\tan 2\theta = \dfrac{2b}{a-c} \gg 1 \quad \text{for} \quad a \sim c \text{ and, or } a, c \ll b$

and masses $m_{1,2} \simeq \dfrac{a+c \pm 2b}{2}$

Example: mu-tau symmetry

Large theta23 motivates to consider the mu-tau symmetry.

$$\mathcal{M}_\nu = \begin{pmatrix} a & b \\ b & a \end{pmatrix}$$

The mixing is given by $\tan 2\theta = \frac{2b}{0} = \infty \Rightarrow \theta_{23} = 45^o$

For 3 generations, this mass matrix respects the symmetry

$$\mathcal{M}_\nu = \sqrt{\Delta m_A^2} \begin{pmatrix} \sim 0 & a\epsilon & a\epsilon \\ a\epsilon & 1+\epsilon & 1 \\ a\epsilon & 1 & 1+\epsilon \end{pmatrix}$$

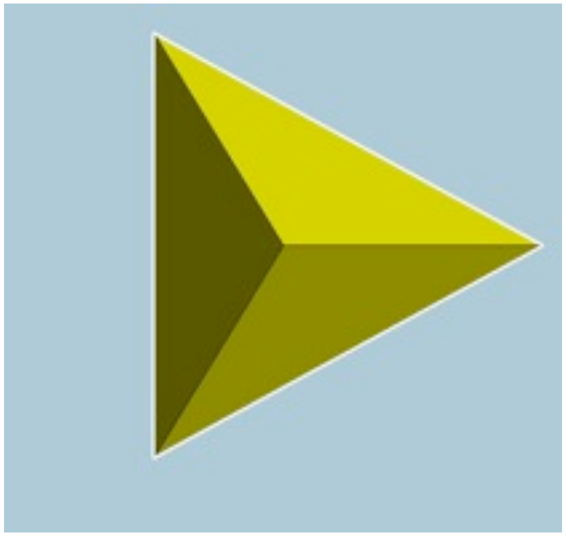
leading to $\theta_{23} = \frac{\pi}{4} - \frac{\Delta m_\odot^2}{\Delta m_A^2}$ $\qquad \theta_{13} \sim \epsilon^2 \sim \frac{\Delta m_\odot^2}{\Delta m_A^2} \sim 0.04$

The large value of theta13 needs additional corrections.

Example: a discrete symmetry A4

An example of discrete symmetry: Z2 (reflections).

A4 is the group of even permutations of (1234). This is a very studied example of discrete symmetry. It is the invariant group of a tetrahedron.



The resulting mass matrices are

$$M_l = v\frac{v_{Hd}}{\Lambda}\begin{pmatrix} y_e & y_e & y_e \\ y_\mu & y_\mu e^{i4\pi/3} & y_\mu e^{i2\pi/3} \\ y_\tau & y_\tau e^{i2\pi/3} & y_\tau e^{i4\pi/3} \end{pmatrix} \qquad M_\nu = \frac{v_u^2}{\Lambda^2}\begin{pmatrix} a & 0 & 0 \\ 0 & a & d \\ 0 & d & a \end{pmatrix}$$

The two matrices can be diagonalised and the resulting mixing matrix is the TBM one: $U_{\mathrm{PMNS}} = U_e^\dagger U_\nu$.

Various strategies and ideas: can be employed to understand the observed pattern (many many models!).

- Texture zero models with

$$\theta_{12,23,13} = \text{function}(\underbrace{\frac{m_e}{m_\mu}}_{\text{too small}}, \ldots, \frac{m_1}{m_2})$$

- Flavour symmetries

- Complementarity between quarks and leptons

$$\theta_{12} + \theta_C \simeq 45^o$$

- Anarchy (all elements of the matrix of same order).

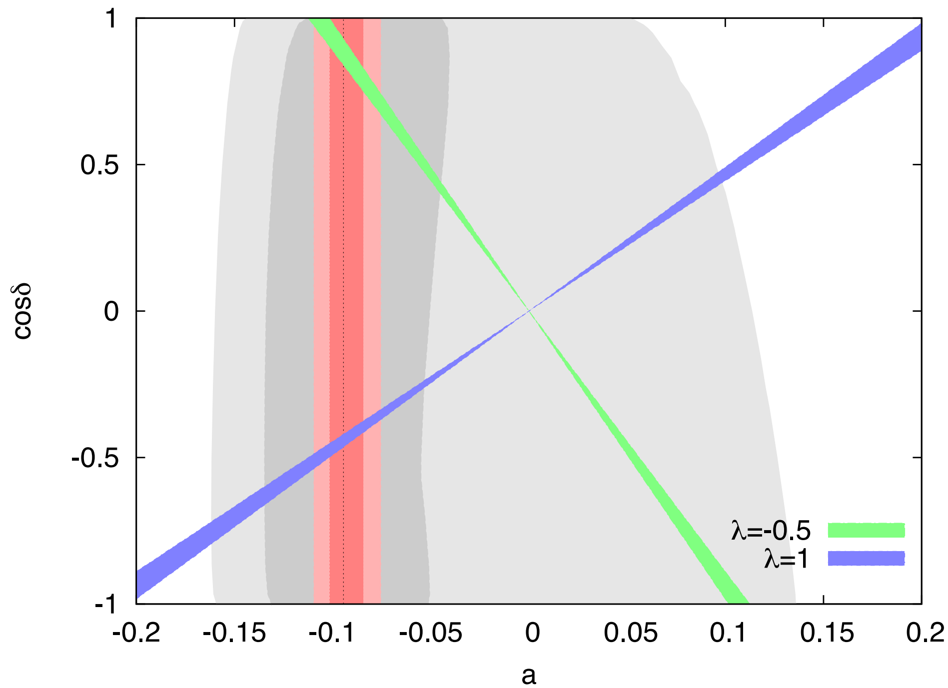
The models predict specific values for the mixing angles and specific relations between the deviations from special values $\theta_{23} \sim 45^o, \theta_{13} \sim 0^o$.

Different flavour models can also lead to predictions for the value of the delta phase:

- Sum rules: $\sin\theta_{12} = \frac{1+s}{\sqrt{3}}, \quad \sin\theta_{13} = \frac{r}{\sqrt{2}}, \quad \sin\theta_{23} = \frac{1+a}{\sqrt{2}}$ King, 0710.0530

$$a = a_0 + \lambda r \cos\delta + \text{higher orders}$$

- discrete models
- charged lepton corrections to U_ν : $U_{\rm PMNS} = U_e^\dagger U_\nu$



Ballett, King, Luhn, SP, Schmidt, PRD89

M.-C. Chen and Mahanthappa; Girardi et al.; Petcov; Alonso, Gavela, Isidori, Maiani; Ding et al.; Ma; Hernandez, Smirnov; Feruglio et al.; Mohapatra, Nishi; Holthausen, Lindner, Schmidt; see also studies by Altarelli, Alonso, Ballett, Bazzocchi, Brahmachari, Branco, M.-C. Chen, Ding, Felipe, Ferreira, Feruglio, Fonseca, Frigerio, Gavela, Ge, Grimus, Gupta, Hagedorn, Hanlon, Hernandez, Holthausen, Hu, King, Joaquim, Joshipura, Ishimori, Lam, Lavoura, C.-C. Li, Lindner, Luhn, Ludl, B.-Q. Ma, E. Ma, Marzocca, Merle, Merlo, Meroni, Mohapatra, Morisi, Nishi, Ohlsson, Otto Ludl, Pascoli, Patel, Petcov, H. Qu, Rebelo, Repko, Rigolin, Romanino, Roy, Schmidt, Sevilla, Silva-Marcos, Smirnov, Stamou, Stuart, Tanimoto, Valle, Villanova del Moral, Vitale, Wegman, Zhang, Zhou, Ziegler...

Two necessary ingredients for testing flavour models:

- Precision measurements of the oscillation parameters at future experiments (including the delta phase).
- The determination of the mass hierarchy and of the neutrino mass spectrum.

Reference		Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
Anarchy Model:					
dGM	[18]	Either			≥ 0.011 @ 2σ
$L_e - L_\mu - L_\tau$ Models:					
BM	[35]	Inverted			0.00029
BCM	[36]	Inverted			0.00063
GMN1	[37]	Inverted		≥ 0.52	≤ 0.01
GL	[38]	Inverted			0
PR	[39]	Inverted		≤ 0.58	≥ 0.007
S_3 and S_4 Models:					
CFM	[40]	Normal			0.00006 - 0.001
HLM	[41]	Normal	1.0	0.43	0.0044
		Normal	1.0	0.44	0.0034
KMM	[42]	Inverted	1.0		0.000012
MN	[43]	Normal			0.0024
MNY	[44]	Normal			0.000004 - 0.000036
MPR	[45]	Normal			0.006 - 0.01
RS	[46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
		Normal	$\theta_{23} \leq 45°$		0
TY	[47]	Inverted	0.93	0.43	0.0025
T	[48]	Normal			0.0016 - 0.0036
A_4 Tetrahedral Models:					
ABGMP	[49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL	[50]	Normal			0.006 - 0.04
Ma	[51]	Normal	1.0	0.45	0
SO(3) Models:					
M	[52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:					
CPP	[53]	Normal			0.007 - 0.008
		Inverted			≥ 0.00005
		Inverted			≥ 0.032
WY	[54]	Either			0.0006 - 0.003
		Either			0.002 - 0.02
		Either			0.02 - 0.15

Albright, Chen, PRD 74

What is the new physics?

The **new Standard Model** will contain

- new particles at a new physics scale
- new interactions.

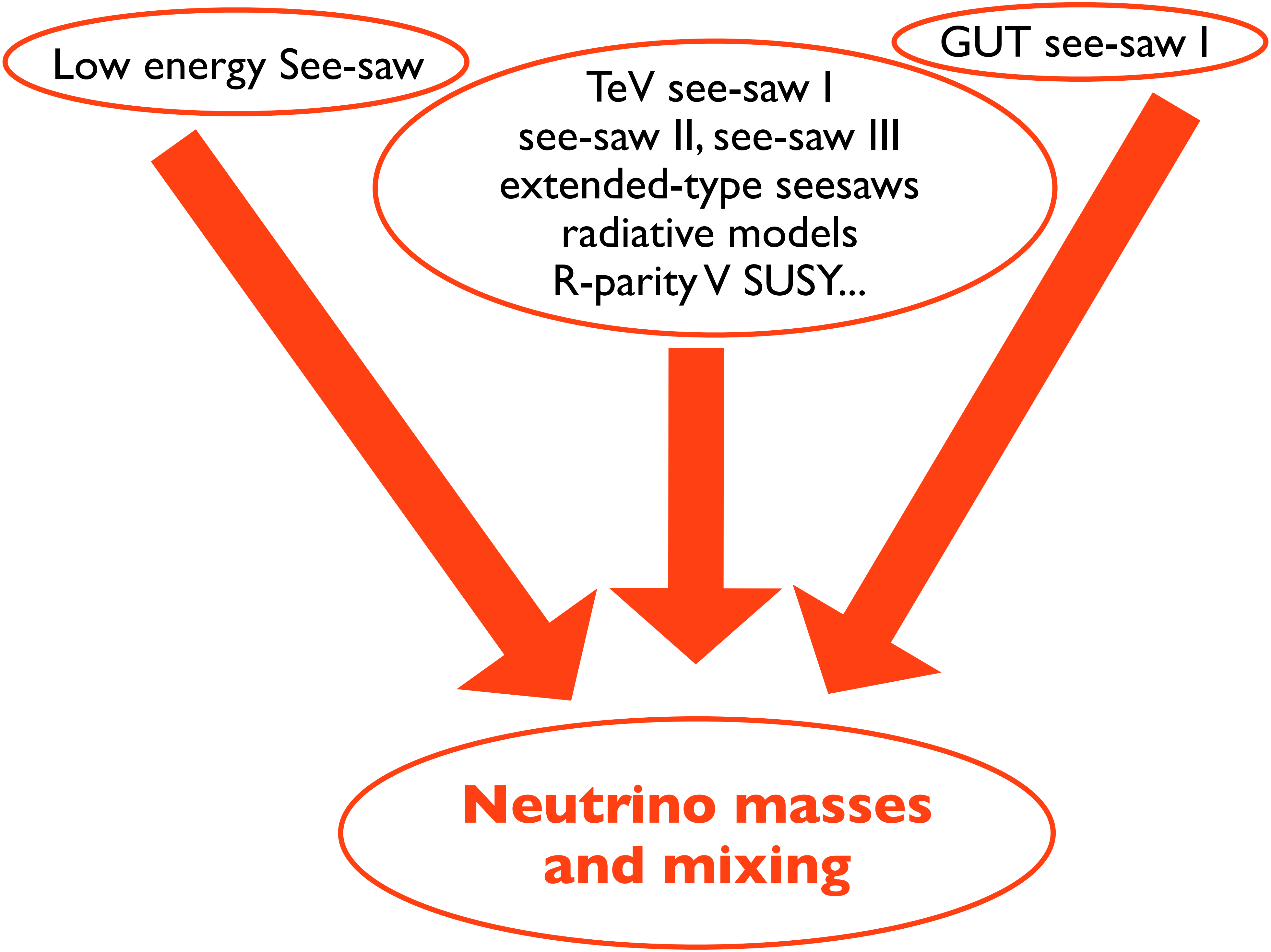
sub-eV eV keV MeV GeV TeV GUT scale

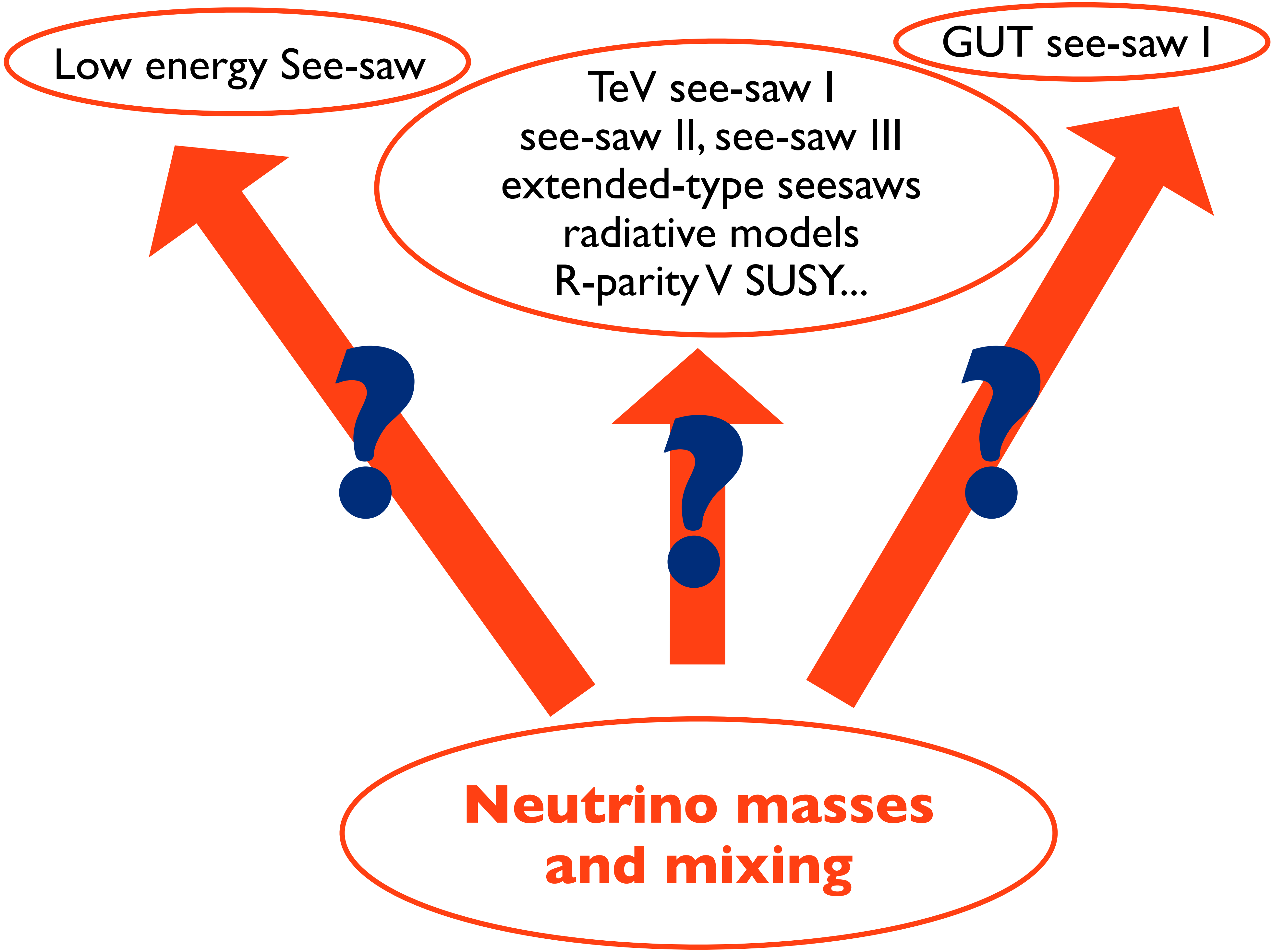
See-saw I (tiny couplings)

GUT see-saw I

TeV see-saw I (small couplings)
see-saw II, see-saw III
extended-type seesaws
radiative models
R-parity V SUSY...

Coupling with the dark sector. Neutrinos can be a portal to new physics: $\mathcal{L}_\nu = y \, \bar{L} \cdot H \; \text{new}$


Low energy See-saw
TeV see-saw I
see-saw II, see-saw III
extended-type seesaws
radiative models
R-parity V SUSY...
GUT see-saw I
Neutrino masses
and mixing


Low energy See-saw
TeV see-saw I
see-saw II, see-saw III
extended-type seesaws
radiative models
R-parity V SUSY...
GUT see-saw I
?
?
?
Neutrino masses
and mixing

Complementarity with other searches

There are many (direct and indirect) signatures of these extensions of the SM.

Neutrino masses

Signatures

Indirect signals (proton decay)

Peak searches

Direct signals in colliders

Charged lepton flavour violation

Kinks in beta decay

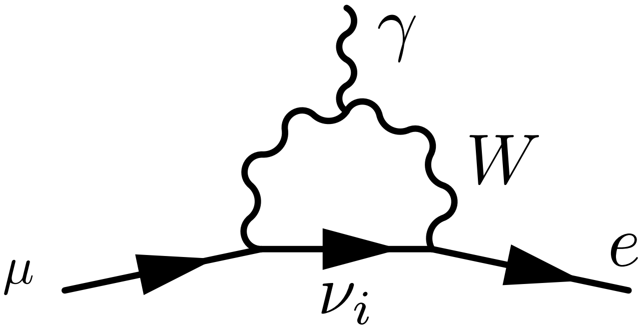
Nuless 2beta decay

Leptogenesis

Establishing the origin of neutrino masses requires to have as much information as possible about the masses and to combine it with other signatures of the models.

Charged lepton flavour violation

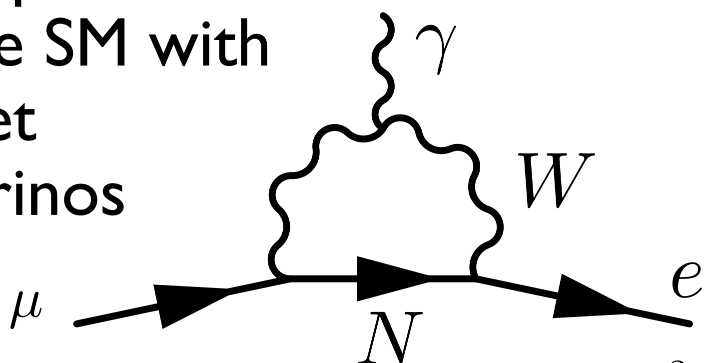
CLFV plays a special role. Neutrino masses induce LFV processes but they are very suppressed.



$$Br(\mu \to e\gamma) \sim \frac{3\alpha}{32\pi} \Big(\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta^2 m_{i1}}{m_W^2}\Big)^2 \sim 10^{-53}$$

Any observation of CLFV would show new physics BSM and provide clues on the origin of neutrino masses.

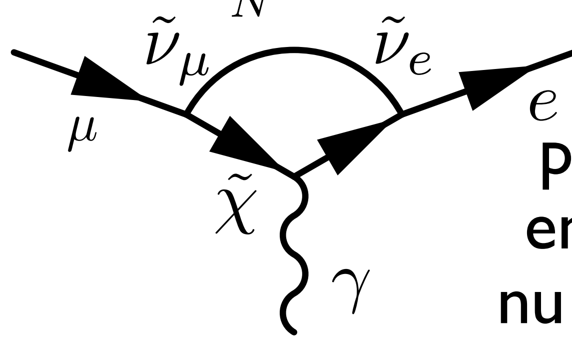
Example: extension of the SM with singlet neutrinos N



$$Br(\mu \to e\gamma) \sim \frac{3\alpha}{8\pi} \Big(\sum_j U^*_{\mu j} U_{ej} g\big(\frac{M_N^2}{m_W^2}\big)\Big)^2$$

Example: SUSY see-saw

$$Br \propto \Big|\sum_N Y^*_{N\mu} Y_{Ne} \ln(m_0/m_N)\Big|^2$$



The same parameters enter in LFV, nu masses and leptogenesis.

Borzumati, Masiero

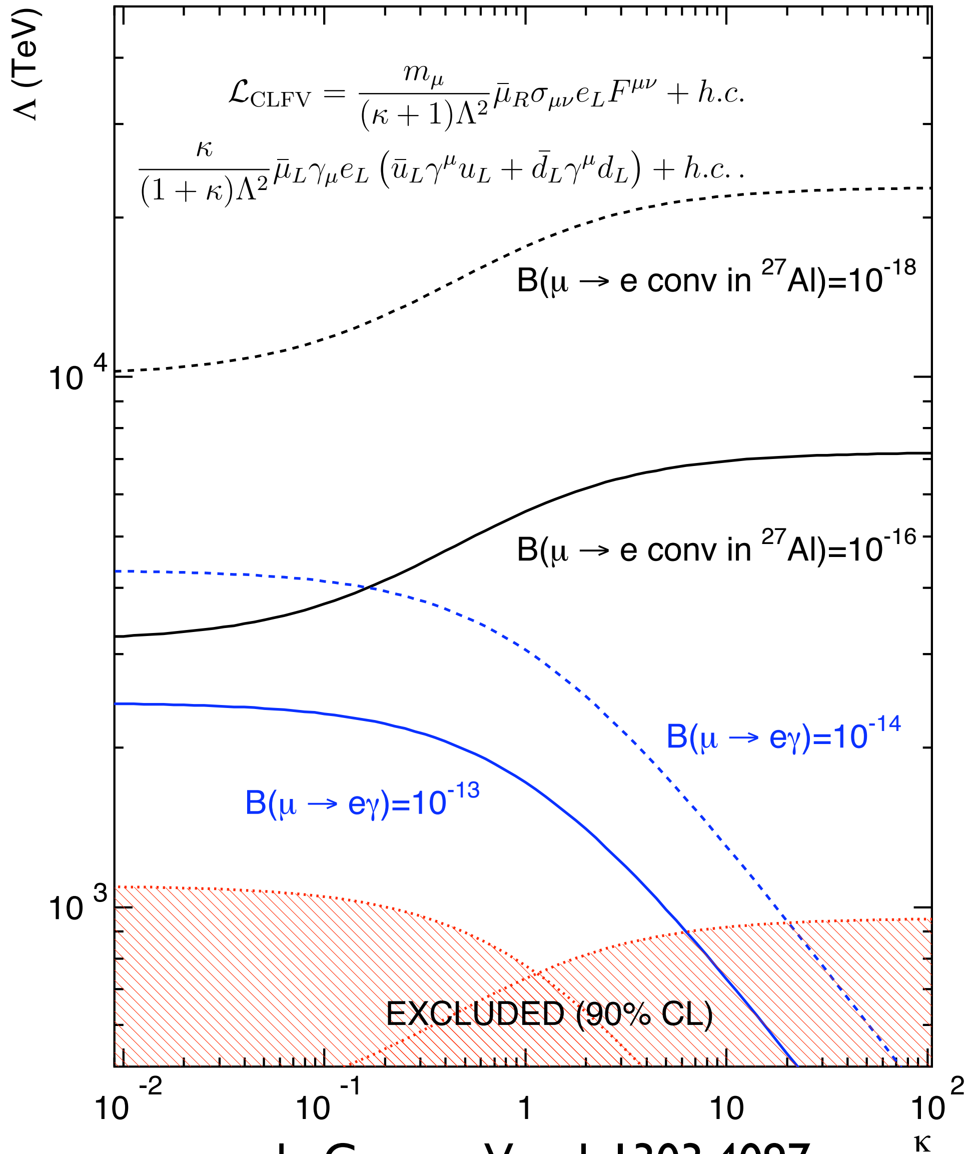
Many models of neutrino masses lead to sizable LFV:

Models at the TeV scale with large mixing

Radiative neutrino mass models

SUSY GUT see-saw models

Extra D, extra Higgs etc.



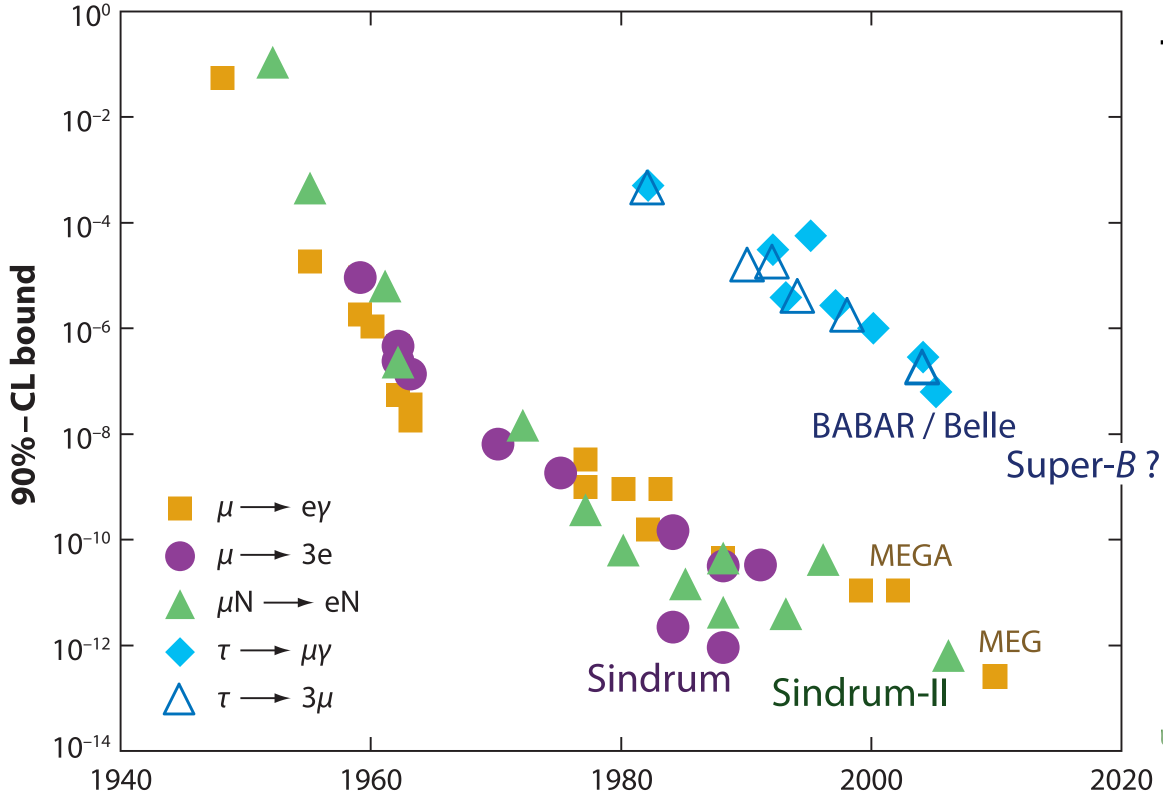
de Gouvea, Vogel, 1303.4097

Other processes can also take place:

- $\mu - e$ conversion
- $\mu \to eee$
- LFV τ decay

Their relative Br depend on the underlying new physics BSM and flavour structure.

Searches for charged lepton flavour violation processes



T. Hambye, update of Marciano, Mori 09

mu->e gamma

MEGII at PSI

One order of magnitude improvement

mu-> 3e

Mu3e at PSI

Sensitivity: Br< 10^{-16}

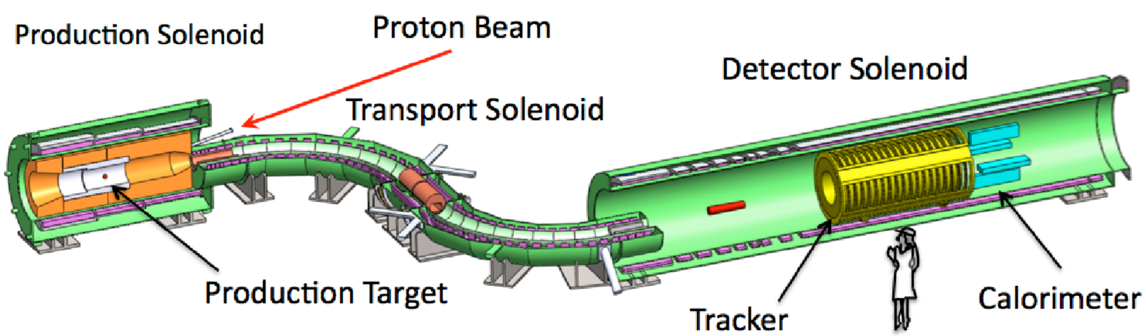
mu-e conversion:

COMET and PRISM

Sensitivity: Br< 10^{-18}

Mu2e

Sensitivity Br< 10^{-17}



11 July 2012: Approval of CD-1 by Office of Science Director

May 2014: strongly endorsed by P5.

http://mu2e.fnal.gov/

Leptogenesis and the Baryon asymmetry

There is evidence of the baryon asymmetry:

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.14 \pm 0.08) \times 10^{-10}$$

Planck, 1303.5076

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

- B (or L) violation;

- C, CP violation;

- departure from thermal equilibrium.

Leptogenesis and the Baryon asymmetry

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Planck, 1303.5076

In order to generate dynamically a baryon asymmetry, the Sakharov's conditions need to be satisfied:

Neutrinoless double beta decay

- B (or L) violation;

LBL

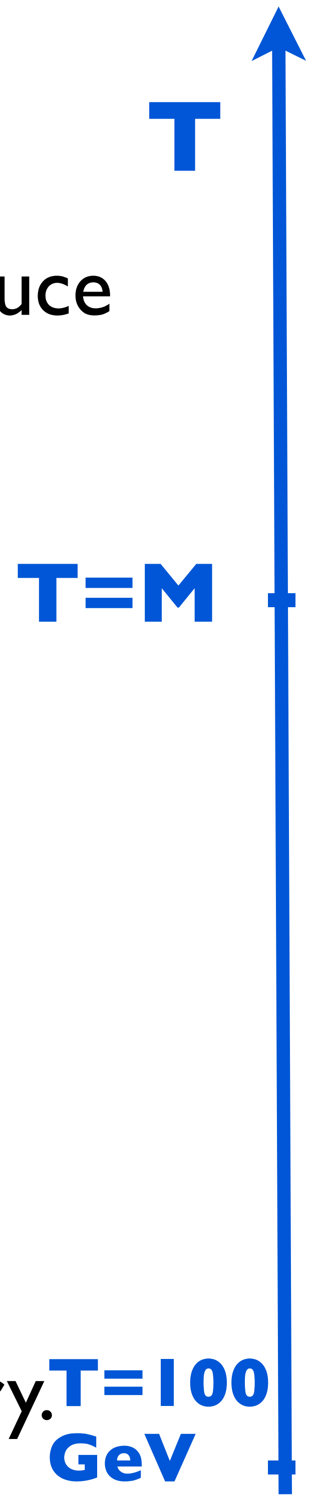
- C, CP violation;

Expansion of the Universe

- departure from thermal equilibrium.

Leptogenesis in models at the origin of neutrino masses

Leptogenesis in see-saw type I



- At T>M, the right-handed neutrinos N are in equilibrium thanks to the processes which produce and destroy them:

$$N \leftrightarrow \ell H$$

- When T<M, N drops out of equilibrium

$$N \to \ell H \qquad\qquad N \to \ell^c H^c$$

- A lepton asymmetry can be generated if

$$\Gamma(N \to \ell H) \neq \Gamma(N \to \ell^c H^c)$$

- Sphalerons convert it into a baryon asymmetry.

Fukugita, Yanagida, PLB 174; Covi, Roulet, Vissani; Buchmuller, Plumacher; Abada et al., ...

In order to compute the baryon asymmetry:

1. evaluate the CP-asymmetry

$$\epsilon \equiv \frac{\Gamma(N \to \ell H) - \Gamma(N^c \to \ell^c H^c)}{\Gamma(N \to \ell H) + \Gamma(N^c \to \ell^c H^c)}$$

2. solve the Boltzmann equations to take into account the wash-out of the asymmetry

$$Y_L = k\epsilon$$

3. convert the lepton asymmetry into the baryon one

$$\boxed{Y_B = \frac{k}{g^*} c_s \epsilon \sim 10^{-3} - 10^{-4} \epsilon}$$

For T < 10^{12} GeV, flavour effects are important.

Is there a connection between low energy CPV and the baryon asymmetry?

The general picture

ϵ depends on the CPV phases in Y_ν

$$\epsilon \propto \sum_j \Im(Y_\nu Y_\nu^\dagger)^2_{1j} \frac{M_j}{M_1}$$

and in the U mixing matrix via the see-saw formula.

$$m_\nu = U^* m_i U^\dagger = -Y_\nu^T M_R^{-1} Y_\nu v^2$$

Let's consider see-saw type I with 3 NRs.

High energy

M_R	3	0
Y_ν	9	6

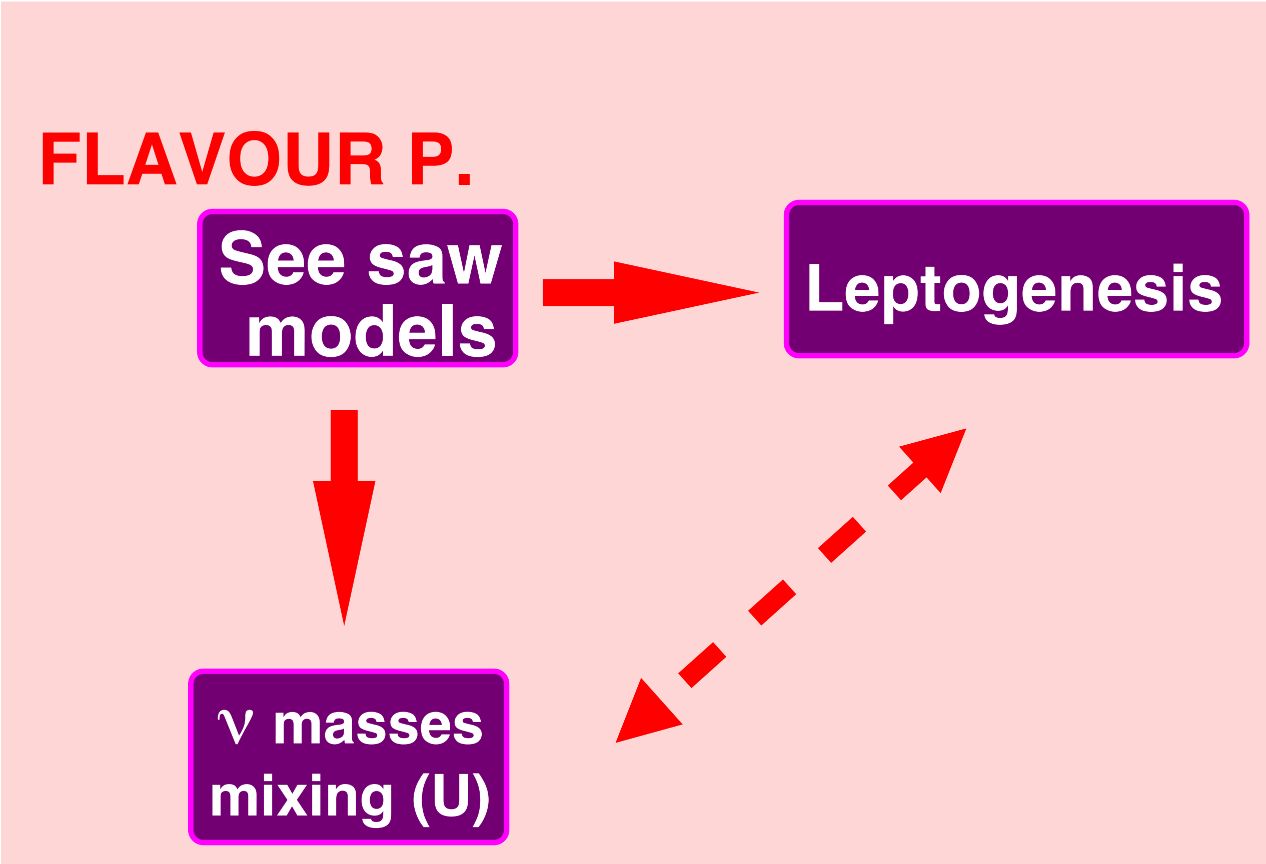
Low energy

m_i	3	0
U	3	3

3 phases missing!

In understanding the origin of the flavour structure, the see-saw models have a reduced number of parameters.

It may be possible to predict the baryon asymmetry from the Dirac and Majorana phases.

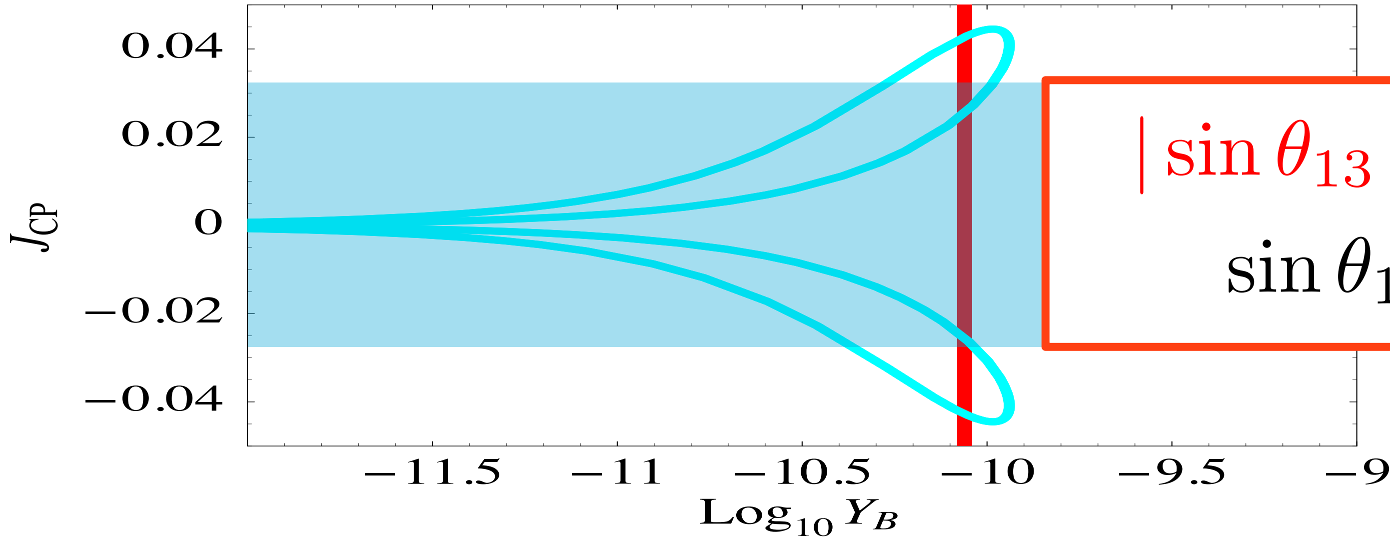


Does observing low energy CPV imply a baryon asymmetry?

It has been shown that, thanks to flavour effects, the low energy phases enter directly the baryon asymmetry.

Example in see-saw type I, with NH (m1<< m2 <<m3), M1<M2<M3, M1~5 10^11 GeV:

$$\epsilon_\tau \propto M_1 f(R_{ij}) \left[c_{23} s_{23} c_{12} \sin\frac{\alpha_{32}}{2} - c_{23}^2 s_{12} s_{13} \sin(\delta - \frac{\alpha_{32}}{2}) \right]$$



$$|\sin\theta_{13}\sin\delta| > 0.11$$

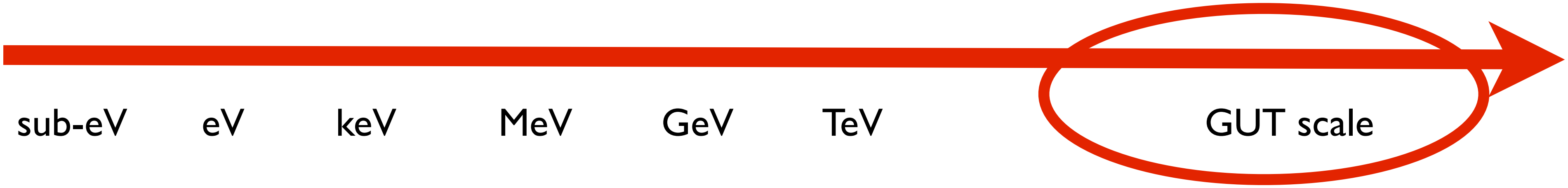
$$\sin\theta_{13}|_{\exp} \simeq 0.15$$

SP, Petcov, Riotto, PRD75 and NPB774

Large theta13 implies that delta can give an important (even dominant) contribution to the baryon asymmetry. Large CPV is needed and a NH spectrum.

Observing L violation and CPV would constitute a strong hint in favour of leptogenesis as the origin of the baryon asymmetry, although not a proof.

What is the new physics scale?



Neutrino masses

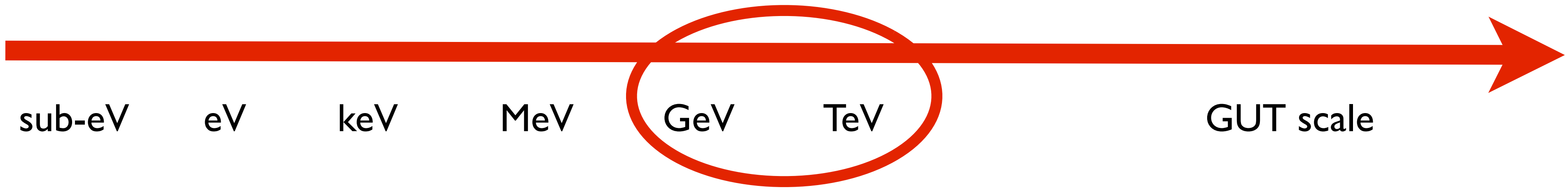
Signatures

Charged lepton flavour violation, in SUSY models

Proton decay

Leptogenesis

What is the new physics scale?



Signatures

Neutrino masses

Neutrinoless double beta decay

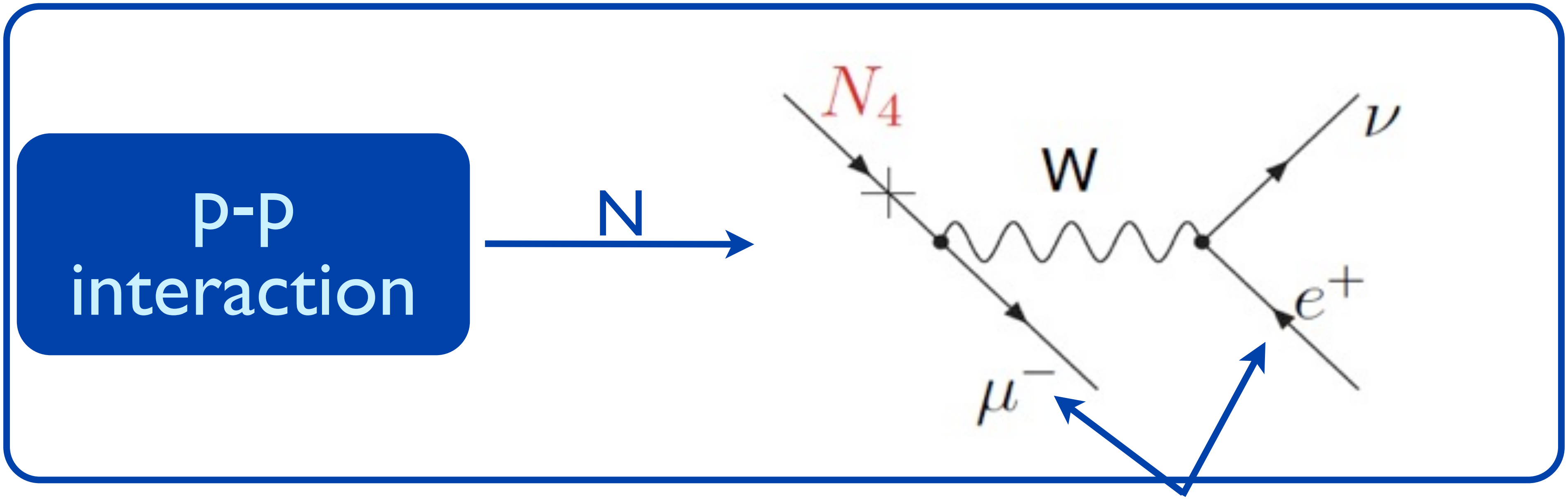
Charged lepton flavour violation

Direct signals in colliders

Leptogenesis with enhancements of CPV effects

Direct searches at the TeV scale

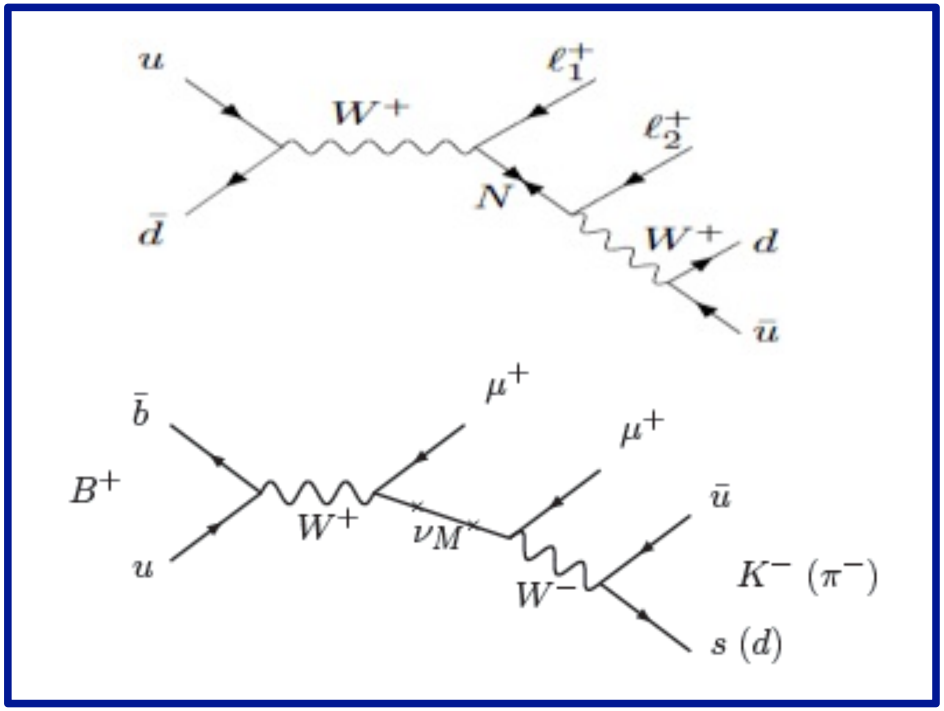
- LNV: same-sign dilepton signal with no missing energy
- multilepton production.



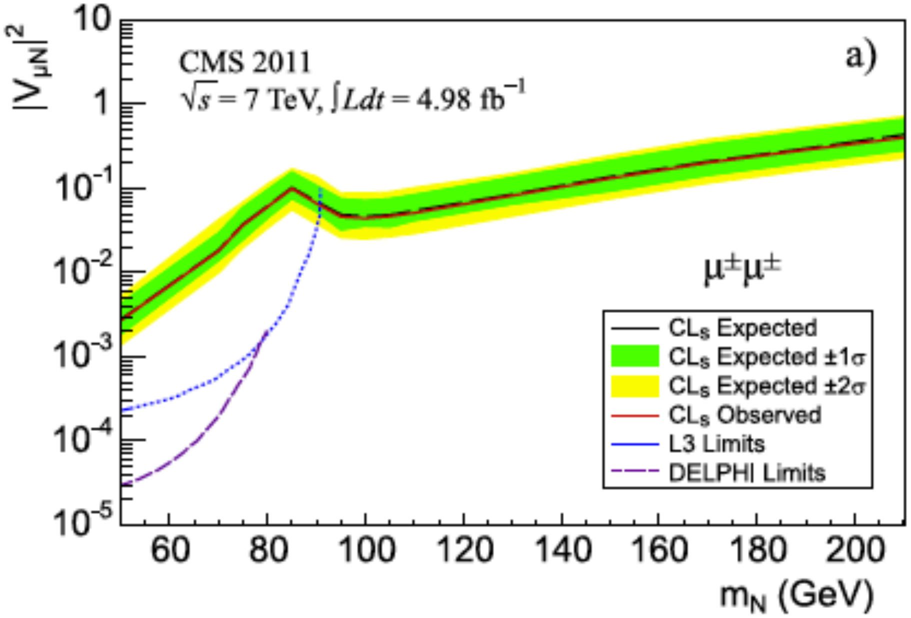
visible particles: photons, electrons, muons, pions....

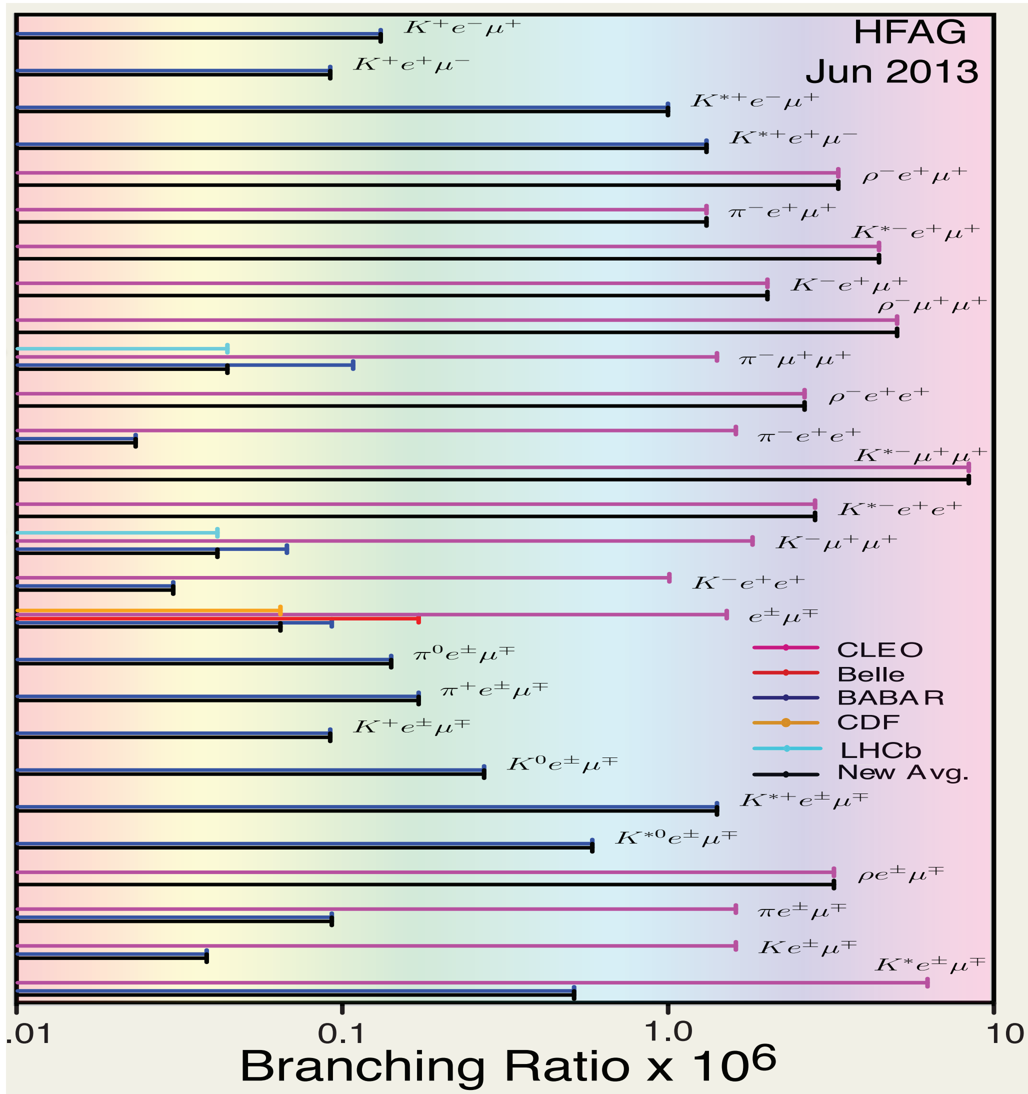
The decay length is controlled by the mixing angle and the branching ratios by SM interactions (and kinematics).

Searches for LNV decays at colliders



ATLAS, CMS and LHC-b have already put new bounds.





From Lafferty, talk at UKHEP Forum 13

What is the new physics scale?

sub-eV eV keV MeV GeV TeV GUT scale

Signatures

Neutrino masses

Peak searches

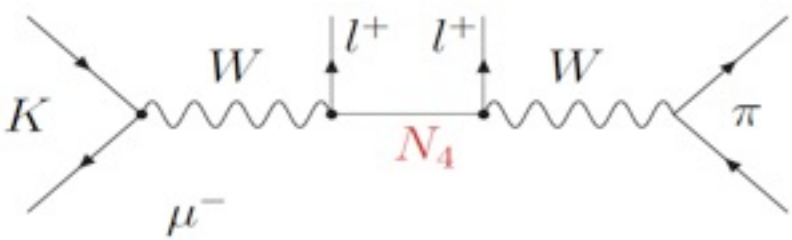
Dark Matter: WDM

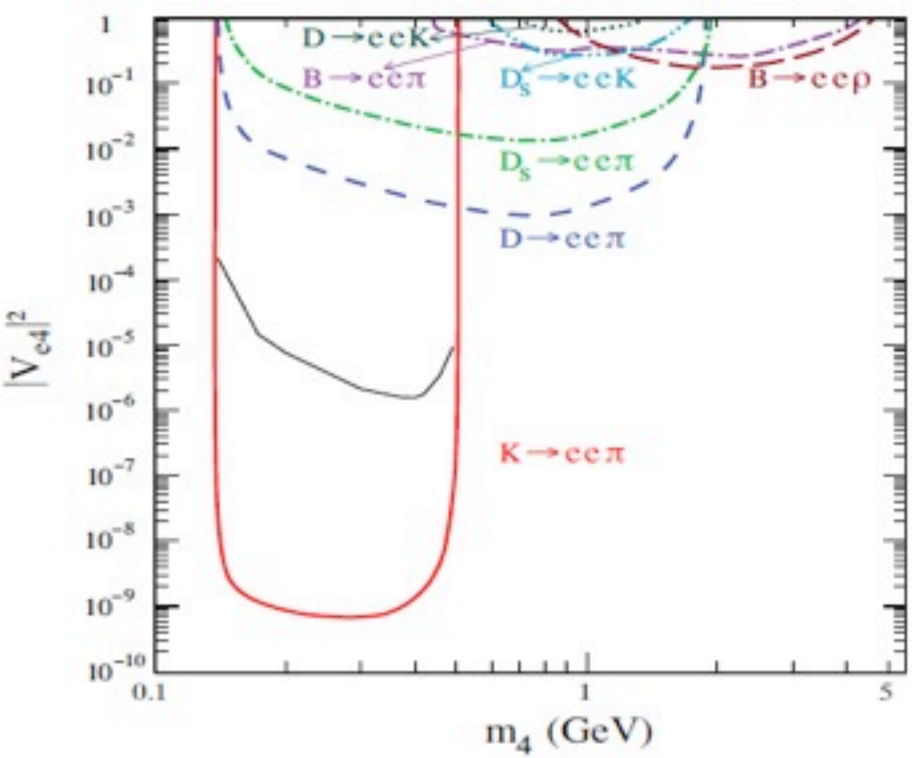
Kinks in beta decay

Neutrinoless double beta decay

Rare tau and meson decays

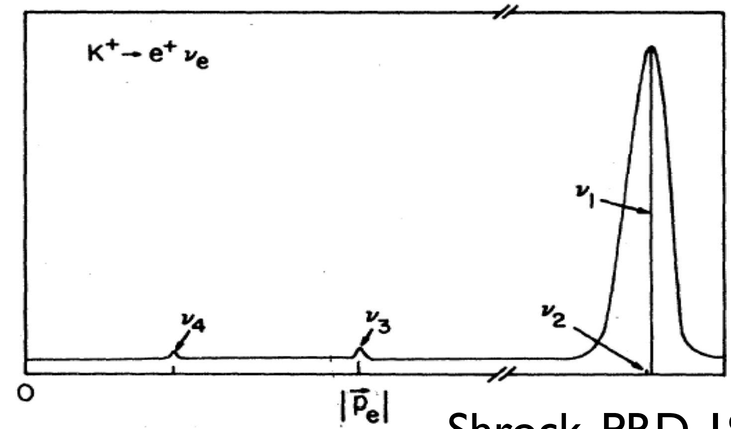
Tau and Meson decays get resonantly enhanced for M~ GeV.





Atre, Han, Pascoli, Zhang, 0901.3589

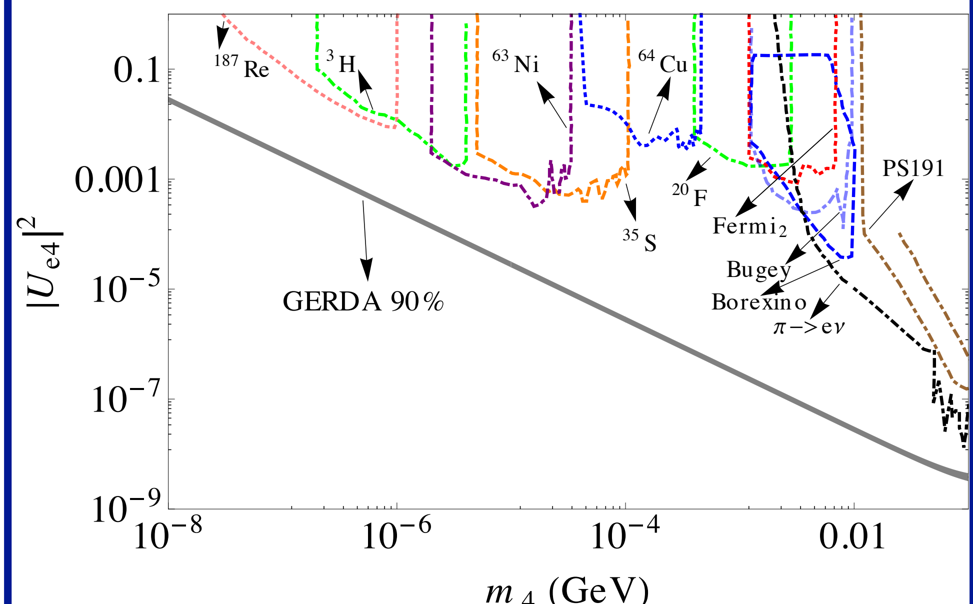
Peak searches



Shrock, PRD 1980

For M~10-100MeV

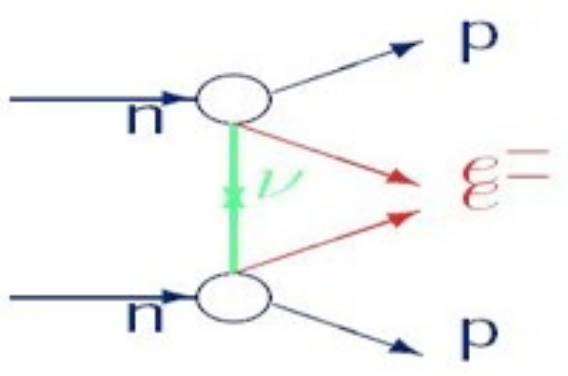
Kinks in beta decays



Mitra, SP, Wong, 1310.6218

Neutrinoless double beta decay

As for light neutrinos, sterile neutrinos, if Majorana, will induce neutrinoless double beta decay.



The half-life time depends on neutrino properties.

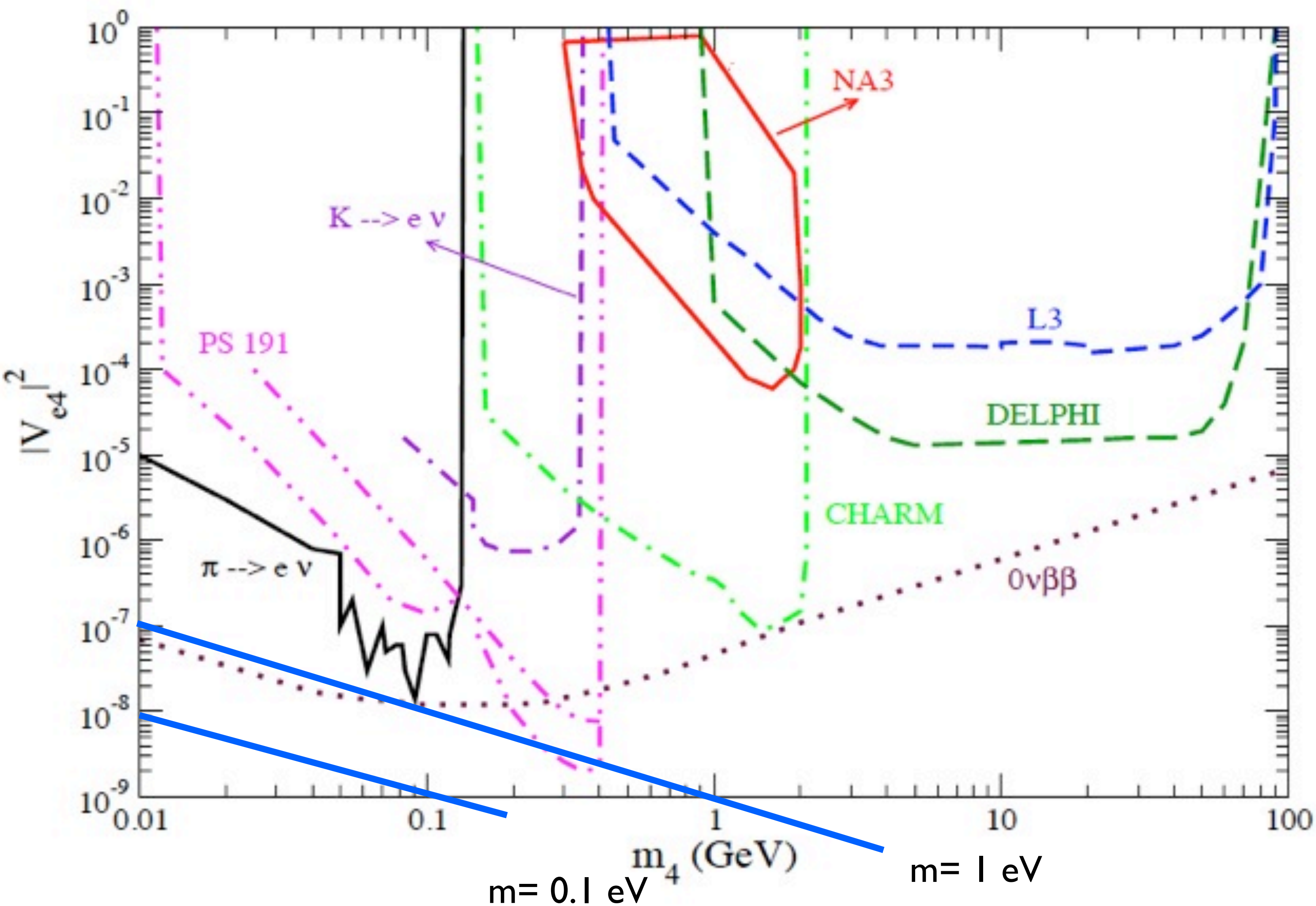
$$(T^{1/2}_{0\nu})^{-1} \propto G_{0\nu} \left| \sum_i NME_i \langle m \rangle_i \right|^2$$

If the masses are below 100 MeV, their effects are not suppressed

$$|<m>| \equiv \left| \sum_{\rm light} m_i U_{ei}^2 + m_4 |U_{e4}|^2 e^{i\alpha_{41}} \right|$$

The NME behaviour changes at p~100 MeV, the scale of the process. In most cases they are subdominant as the NME for heavy particles suppress their contribution w.r.t. the long range processes.

Particles can be produced directly but very small Yukawa couplings are required or specific cancellations in the masses (e.g. extended see-saw).



Atre, Han, SP, Zhang, 0901.3589

What is the new physics scale?

Signatures

Neutrino masses

Neutrino oscillations

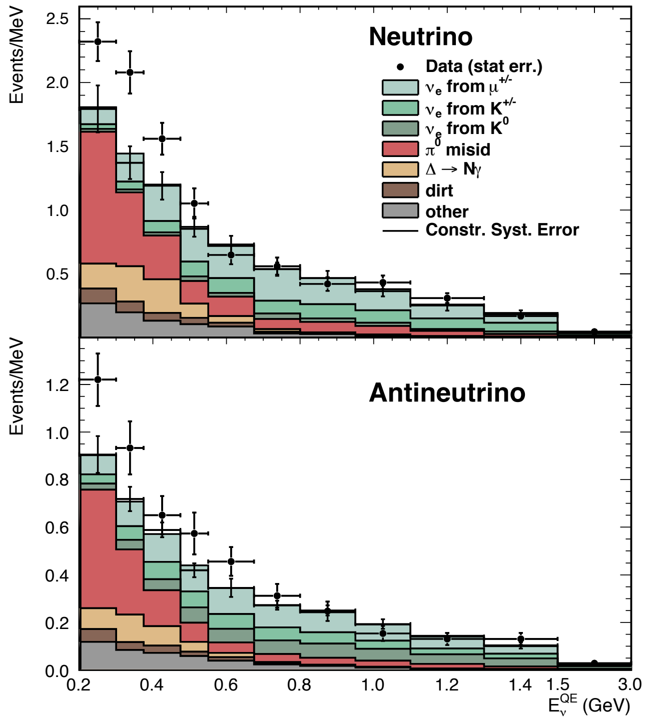
Dark Matter: HDM

Kinks in beta decay

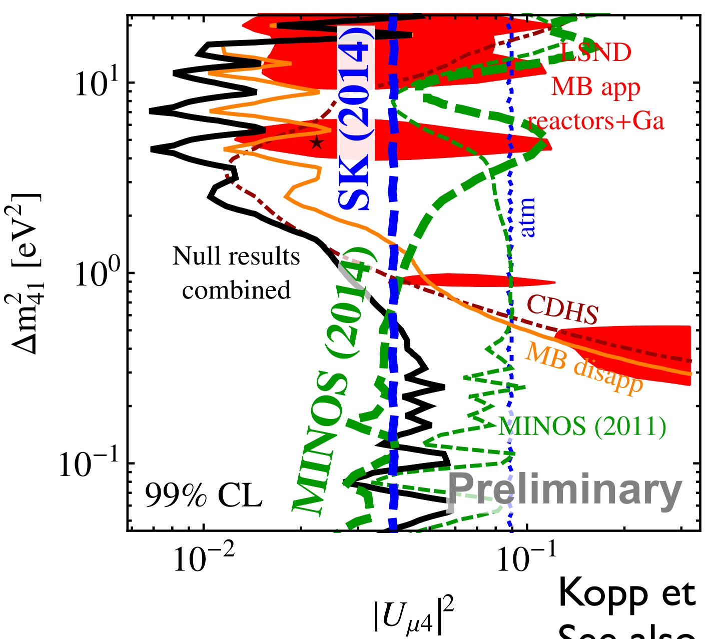
Neutrinoless double beta decay

Non-standard effects: sterile neutrinos

MiniBooNE, PRL 110



MiniBooNE was designed to test the LSND excess. It found an excess of events at low energy. MicroBooNE is going to probe these hints.
Reactor anomaly: A recomputation of the reactor fluxes seems to indicate neutrino disappearance.



There is a significant tension between appearance and disappearance data. Many plans to test these anomalies in short baseline oscillations: nuclear decays, reactors and accelerators.

Kopp et al., JHEP 1305 2013 + preliminary at Neutrino 2014
See also Giunti et al., 1308.5288, Conrad et al., 1207.4765

If light sterile neutrinos are found, it would change our perspective on neutrino mass models and the flavour problem.

1. Do they give mass to the light neutrinos, via a low energy see-saw? Testable in neutrinoless double beta decay.

$$\begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} = U_{\text{total}} \begin{pmatrix} m_{\text{light}} & 0 \\ 0 & m_4 \end{pmatrix} U_{\text{total}}^T$$

$$0 = \sum_i U_{ei} m_i U_{ei}$$

Although Majorana neutrinos, no signal in neutrinoless double beta decay!

2. Why are they so light? Is there a common origin for sterile neutrino and standard neutrino masses?
3. What is the origin of the mixing pattern?
4. Are there new sources of CPV?
5. What is their effect on the evolution of the Universe?

Conclusions

- Neutrino masses are the first evidence of Physics BSM and they provide a new complementary window w.r.t. collider and flavour physics searches.

- It is necessary to have precise information on the values of the masses and on the mixing angles and CPV phase. This is crucial to understand the origin of the leptonic flavour structure (e.g. flavour symmetries).

- Determining the New Standard Model (nuSM), responsible for neutrino masses, is the ultimate goal. It requires complementary information: CLFV, leptogenesis, direct searches at TeV scale and below, low energy probes (e.g. short baseline neutrino oscillations).